

# Assessment of Satellite Communications Quality Study

## Final Report NAS3-23790

S. J. Campanella

COMSAT Laboratories  
Clarksburg, Maryland

## Addendum 1

### Impact of Propagation Delay on Data Transmission

S. J. Campanella and D. M. Chitre

COMSAT Laboratories  
Clarksburg, Maryland

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# ASSESSMENT OF SATELLITE COMMUNICATIONS QUALITY STUDY

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S. J. CAMPANELLA

COMSAT LABORATORIES  
CLARKSBURG, MARYLAND

## ABSTRACT

The single factor that irrevocably distinguishes geostationary satellite telephony transmission from terrestrial transmission is the greater propagation delay over satellite links. This difference has always provoked vigorous debate over the impact of delay on the subscribers using services incorporating satellite links. This paper addresses the issue from a variety of directions including human factors studies, laboratory subjective tests that evaluate delay with and without echo, and field tests that obtain data on the opinion of subscribers regarding the quality of service of operational circuits in both national US domestic and international trans-Atlantic networks. The tests have involved the use of both echo suppressors and echo cancellers.

As a rule, echo on any long distance circuit, be it short delay submarine fiber cable or long delay satellite, renders the circuit unacceptable. The real problem in transmission is echo, not delay. Experience indicates that on circuits in both domestic and international service, echo control devices that do not function properly cause far more difficulty in the form of continuous echo, spurts of echo and chopping of speech for subscribers than is caused by propagation delay. Careful maintenance of the terminating connections between the subscriber and the long distance transmission facility is important to achieving performance acceptable to the subscriber.

Echo cancellers operating with properly maintained terminations virtually eliminate echo. Echo cancellers have been implemented using large scale integrated circuitry (LSIC) and are now relatively inexpensive and readily available from many US and foreign manufacturers. The results of numerous tests under

laboratory and field conditions show conclusively that elimination of echo results in fully acceptable performance of single-hop satellite circuits and significantly enhances the acceptability of double hop circuits.

Echo cancellers inherently benefit the subscriber at the opposite end. This creates a situation that is unfair to the subscribers of the country installing them if the correspondent country does not also install them as the subscribers in the correspondent countries benefit, while those in the country installing the echo canceller do not. Administrations must be urged to reciprocate in improving their terminations to be fair to their corresponding customers. Presently, all international US terminations are equipped with echo cancellers; however, most other countries have not reciprocated. Consequently US customers are not benefiting, while those in other countries are!

As the world moves into the ISDN era and digital circuits are extended back to the subscriber's telephone set, the major cause of echo, the two wire/four wire termination, will disappear. This echo free environment will result in fully acceptable performance of satellite telephony networks.

Data communications over satellite links is another issue of concern that needs to be understood. The matter is treated in a separate annex. Propagation delay, from the point of view of transport delay between users computer terminals, is not in itself a cause of unacceptability. Rather, the difficulties arise in the data communications protocols used to assure error-free transmission between computer terminals and the response of these to propagation delay, link error rate and transmission rate. Selection of appropriate protocol procedures essentially eliminates any deleterious effect of single and double hop satellite link delays and link error rate. However, the correct procedures do exact additional memory on the transmit and receive sides of packet transmission terminals.

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Propagation delay has been identified as a property of long distance telephone communications since the mid 1920s, when telephone lines first reached coast to coast in the U.S. and the pioneering steps of trans-Atlantic telephone cables were being taken. Evidence of this is contained in a paper by O. B. Blackwell presented to the South West District Meeting of the AIEE in Kansas City, Mo., October 22-24, 1931 and printed in the January 1932 issue of the Bell System Technical Journal<sup>[1]</sup>. The abstract of this paper contains the following:

"Until comparatively recent years the telephone engineer gave little attention to transmission time in his problems. For all practical purposes he could assume that speech was transmitted instantly between the ends of telephone circuits. The rapid extension of the distances over which commercial telephony is given and the introduction of long telephone cables has changed the situation and has introduced time problems in telephone transmission which are of large technical interest and difficulty. As a result, time problems are receiving more consideration in the technical papers published in recent years on transmission. "

This illustrates that the issue of propagation delay and its impact on telephone users has been a matter of concern for over fifty years. Blackwell was specifically addressing telephone communications joining together long lengths of cable in the US and long lengths in Europe with long lengths of intervening submarine cable. Today the issue is still of concern regarding the joining of terrestrial systems by intervening satellite links.

There are two factors that influence conversations between telephone talkers on long distance circuits. The first is echo, which is the result of reflection of a talker's voice signal from the far end of the circuit, and the second is the propagation delay itself. Echo, with delays in excess of a few tens of milliseconds, causes serious interference to conversation rendering it impossible for some talkers to continue conversation. It must be eliminated from long delay circuits. Sources of echo and the means to eliminate them are described later. Propagation delay, which causes responses between

talkers to be delayed longer than normally expected for face to face conversation, is more subtle. Delays between the completion of an utterance by a talker and the reception of a response from a correspondent of less than 200 ms probably pass unnoticed; but longer delays elicit varying amounts of talker reaction ranging from "not perceived" to "perceived but not objectionable" to "objectionable". Numerous subjective tests have been performed to assess how much delay will be tolerated by telephone users. A number of these are described later.

## 1.1 RANGE OF PROPAGATION DELAY.

### 1.1.1 Long Line Segment Delay

The speed of propagation of radio waves in vacuum and the earth's atmosphere is the speed of light, 186,000 miles/s. This fact makes direct line-of-sight terrestrial microwave links the shortest delay communication paths. Transcontinental terrestrial microwave links can traverse the 2,400 mile coast to coast distance of the US, in approximately 13 ms. Geostationary satellite links also use microwave transmission. However, because the satellite is located in an orbit having an altitude of 22,300 miles above the equator, the distance traversed by the radio waves connecting two typical cities in the US. is approximately 51,000 miles resulting in 274 ms propagation delay in each direction of transmission.

Confining radio waves in either a cable or a fiber light guide significantly slows the speed of propagation to approximately  $\frac{2}{3}$  that of light in a vacuum. Thus, a fiber light guide across the US introduces a one-way delay of approximately 20 ms. For the 4,000 mile path across the Atlantic between New Jersey and the UK, as shown in Figure 1, the one-way fiber cable delay is approximately 33 ms and for the 7,500 mile path across the Pacific between the west coast of the US and Japan it is 60 ms.

Satellite links may also be used in a half hop connection in which a satellite link is used in one direction and a terrestrial link in the other. For the trans-Atlantic transmission segment this results in a round trip delay of 307 ms (the sum of 274 ms for the satellite section and 33 ms for the submarine cable section) which is equivalent to a one-way delay of 153.5 ms. This is a significant reduction in the propagation delay compared to the full satellite hop. However, this arrangement is encumbered by the separation of the

paths supporting the two sides of the circuit and the attending complexity of the switching and routing needed to insure that the two sides remain properly associated.

The slowest speed of propagation, found in the H88 loaded twisted pair cable used in some of the longest subscriber loops, is 20,000 miles/s. But this is rarely used on lengths greater than 5 miles, in which case it introduces a propagation delay of only 1/4 ms. Unloaded, twisted-pair customer loops have a propagation speed that is approximately 2/3 that of light in a vacuum.

### 1.1.2 Total End to End Delay

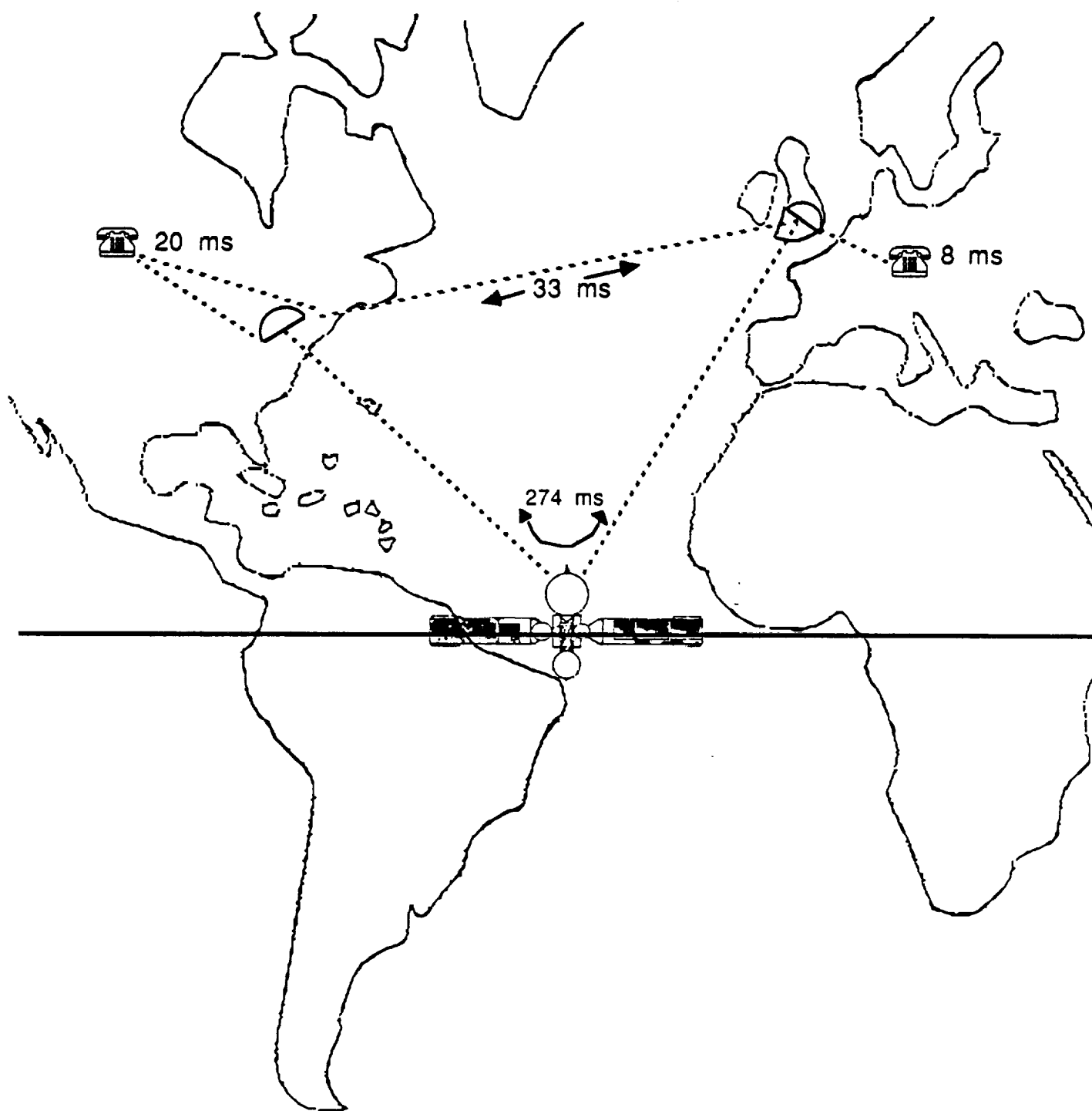
Long distance communications facilities terminate at a location that is some distance from the subscribers and the delay encountered in the end connection becomes significant. The situation for the Atlantic Ocean Region is shown in Figure 1. A call originating on the West coast of the US to a destination in Munich, FRG will encounter an end delay of 20 ms across the US and another end delay of 8 ms in Europe yielding a total subscriber to subscriber delay of 61 ms over trans-Atlantic cable. Replacing the trans-Atlantic cable by a satellite link between the same cable terminations increases this delay to 302 ms. A subscriber in Washington, DC has only 2 ms end delay to New Jersey yielding a total delay of 43 ms by trans-Atlantic cable or 284 ms by satellite to a subscriber in Munich. The satellite delay could be reduced to approximately 276 ms if earth terminals were placed near the origin and destination of the call. These one-way delays may be augmented up to 10 ms by transmission processing.

In summary, the total end-to-end one-way propagation delay ranges from a few tens of ms to 300 ms. Subjective reaction to conversation over this range with and without echo significantly influences the acceptability of the telecommunications service. In later sections, the results of analyses and tests that have attempted to gauge the subjective reaction to delay and echo are presented.

## 1.2 CAUSES OF ECHO

Echo is caused by the reflection of the voice signal from an impedance discontinuity in the telephone signal's transmission path. The principal source of such discontinuities in the switched

**Figure 1. One-Way Delay for AOR Submarine and Satellite Circuits**



telephone network is at the hybrid connection between the two wire customer loops and the four-wire transmission facility<sup>[2]</sup>. Also, additional reflections can be encountered within the network at other junctions between two-wire switches and four wire transmission facilities. Thus, multiple reflections can occur. Typical telephone engineering practice maintains the average return loss of the echo from each hybrid at 11 dB with a standard deviation of 3 dB over the 500 to 2500 Hz portion of the voice-frequency spectrum. Echo traveling in the opposite direction to the signal is referred to as talker echo; that reflected again so that it travels in the same direction as the signal is referred to as listener echo. Subjective sensitivity to echo is a function of the return loss and the delay time. The delay time encountered on US trans-continental terrestrial links is sufficient to require active echo control devices to provide acceptable voice service. Echo control technology has advanced tremendously over the last decade making it possible to virtually eliminate echo as a cause of unacceptable service on all long distance circuits, terrestrial or satellite. Echo control devices designed to limit talker echo may not be suitable for data transmission and additional echo control features are necessary.

When eventually, the ISDN<sup>[3]</sup> or an equivalent concept becomes prevalent, two wire customer loops will begin to disappear and along with them will go the major cause of echo. This will happen because digital transmission, which is inherently four wire (separate path for the receive and send sides of the telephone set) eliminates the offending two wire to four wire hybrid circuit. Only the internal acoustic path of the telephone and the path caused by reflections in the room in which the telephone is located will remain. These can cause low level echo which can be eliminated by echo control devices contained in the telephone set itself. Thus, it can be expected that the ISDN era will ultimately eliminate echo as a problem. However, several decades are likely to pass before the ISDN becomes sufficiently pervasive to eliminate the need for echo control at the switches serving long-line transmission facilities.

### 1.3 VOICE SERVICE IMPAIRMENT DUE TO ECHO

Echo becomes objectionable at relatively short delay. Talker echo merges with the side-tone and is not noticeable for small delays (less than 1 ms). Listener echo becomes noticeable as a "rain barrel" effect with delays of only a few ms. Beyond that, echoes are heard

as distinct signals which become more noticeable as the delay is increased. If echo is not reduced, conversation becomes almost impossible by the time the echo delay is increased to 30-40 ms. Thus, echo can be quite objectionable for delays encountered on US trans-continental and trans-Atlantic calls. Figure 2 is a plot of the minimum echo attenuation necessary for just-tolerable conditions to prevail as a function of delay<sup>[2]</sup>. The curve shows the average tolerance of all listeners to talker echo, although individuals may vary considerably from the average in their judgement.

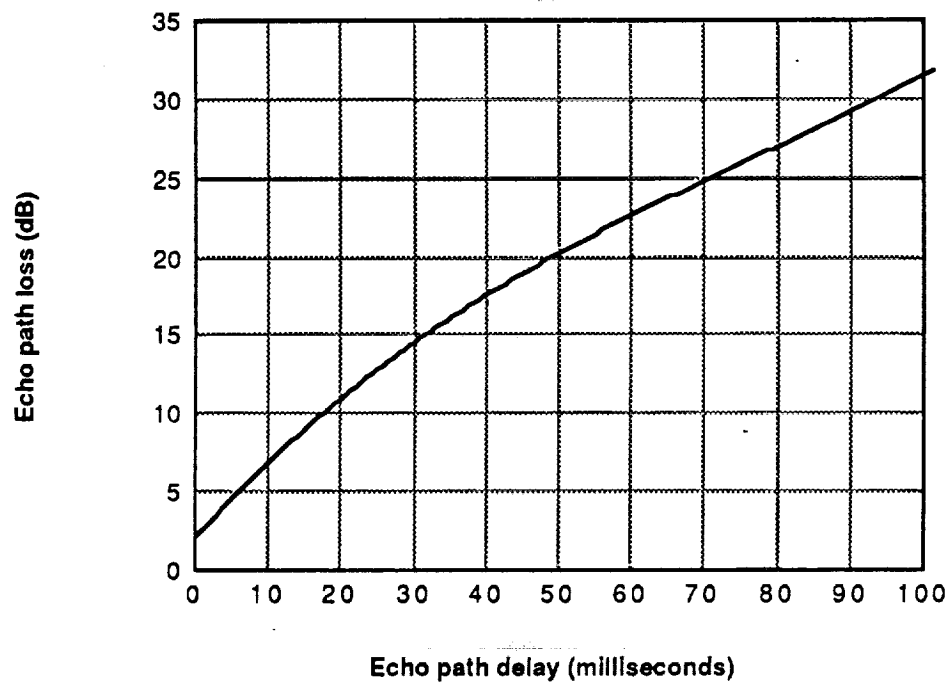
#### 1.4 CONTROL OF ECHO

Passive and active means of limiting echo are used. Passive means refers to the use of metered amounts of loss introduced in the circuit to reduce talker-echo as a function of delay and is accomplished by the Via Net Loss (VNL) rules. Active means are echo suppressors that stop echo by opening the return transmission path and echo cancellers that cancel the echo by generating a replica of the echo and subtracting it from the return path. Because cancellers maintain the continuity of the transmission path and do not switch the path, they perform with far less potential for disrupting the path and accidentally chopping wanted speech or letting echo pass. The superior control of echo cancellers makes them preferred on long-ropagation-delay circuits such as trans-oceanic cable and satellite links. However, their use also improves quality on the shorter long-line terrestrial circuits such as those encountered in large countries and in Europe. Also their rapidly decreasing cost due to LSI implementation is causing echo cancellers to become the preferred method of echo control on all circuits with round trip delays in excess of 45 ms.

Today the majority of US telephone companies use echo cancellers in preference to echo suppressors. However, cancellers are catching on slowly in Europe. A possible cause for this is the following. The customer at the opposite end of the circuit from the location of the echo canceller benefits from the echo protection it provides. European customers are now benefiting from the use of cancellers at the US end of the trans-Atlantic international circuits and are obtaining high quality. They are not motivated to complain to their telephone administrators. Consequently, the European administrators are not motivated to introduce the same improvements in echo control that have been introduced on the US



**Figure 2. Talker Echo Tolerance, Average Observer**



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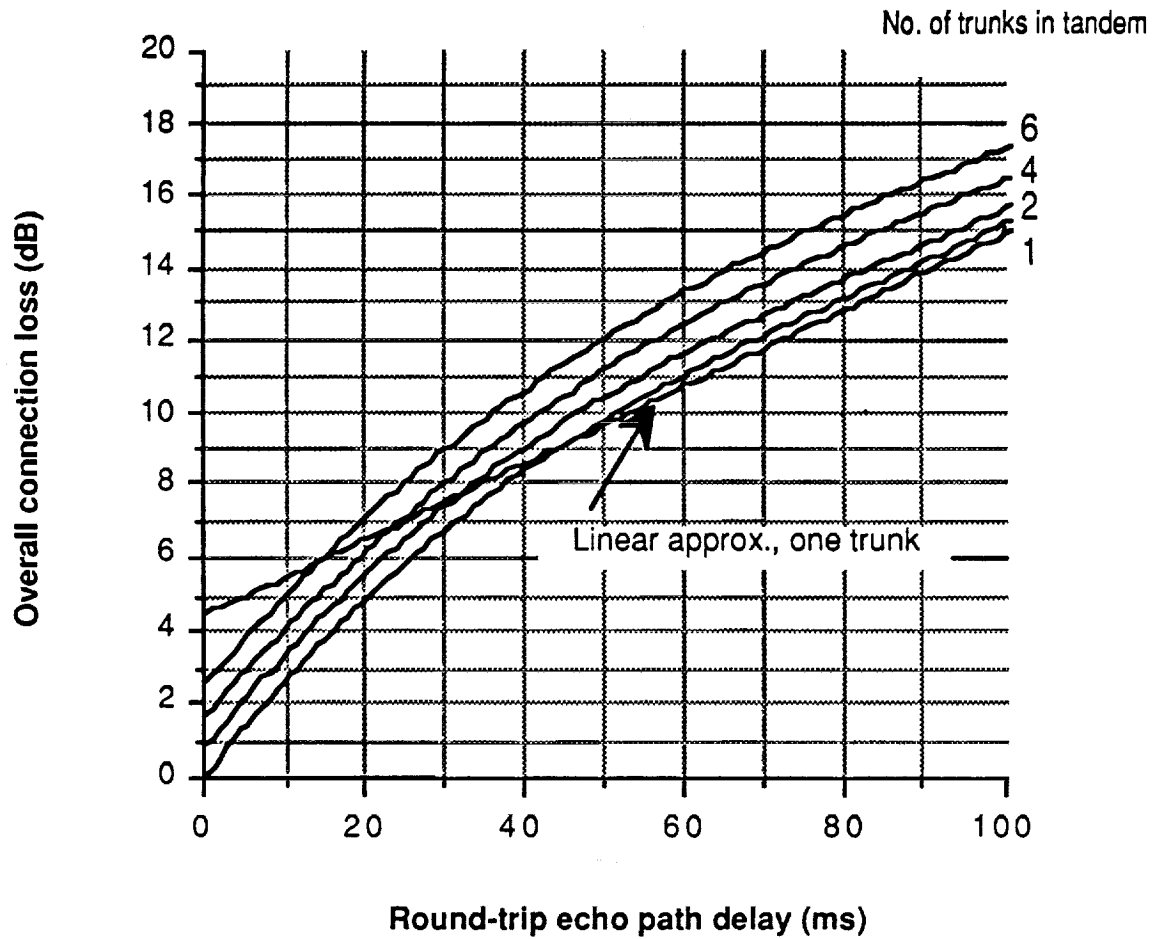
end. The US customers are not benefiting and are experiencing poor service caused by the inferior performance of the older echo suppressors at the European terminations. Unless something is done to cause the European telephone administrators to rectify this situation, the US international customers will continue to receive a lesser quality of service than the European customers.

a)           Via Net Loss Plan

Subjective assessments of the sensitivity of subscribers to echo reveal that for echo path delays less than 100 ms, a circuit delivers acceptable performance provided the overall echo return loss is increased in the proper amount with increasing delay. The curves of Figure 3[2] show the amount of loss that needs to be inserted in the echo path as a function of delay for various numbers of tandem connected trunks. The curves show that for zero delay no loss is needed. This is no surprise since speech heard with no delay is equivalent to hearing your own voice via the combination of the internal body path and the mouth to ear air path. In fact, a typical telephone set deliberately introduces echo of zero delay, called side tone, as a means of controlling the loudness effort exerted by the talker. As the delay is increased, echo becomes a problem. Echo path delay of less than 25 ms is perceived as a hollow, reverberant sound like that created when talking in a large barrel. As the delay increases further, the reflected signal is perceived more and more as a separate echo event. When the echo path delay reaches 100 ms, the reflected signal is clearly discernable as a separate echo. In air this corresponds to a reflection from an object at a distance of 55 feet. The overall echo return loss must be increased as a function of round trip delay as shown in the curves of Figure 3 to maintain the same level of talker satisfaction. This is accomplished by assigning increased trunk losses with increased distance according to a plan referred to as Via Net Loss (VNL) [2, 4]. The VNL plan is represented by the straight line approximation shown in Figure 3. For every 1 dB of loss inserted, the echo is reduced by 2 dB. For round trip delays exceeding 30 ms, VNL operation also requires that echo suppressors or cancellers be inserted.

This gradually metered VNL echo control was originally intended for analog circuit application. It is not suitable for digital networks. Consequently, a modification using a fixed-loss trunk design has been adopted for digital networks in which 3 dB of loss

**Figure 3. Via Net Loss Plan**



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are inserted at both the transmit and receive sides of toll connecting trunks for all connection lengths.

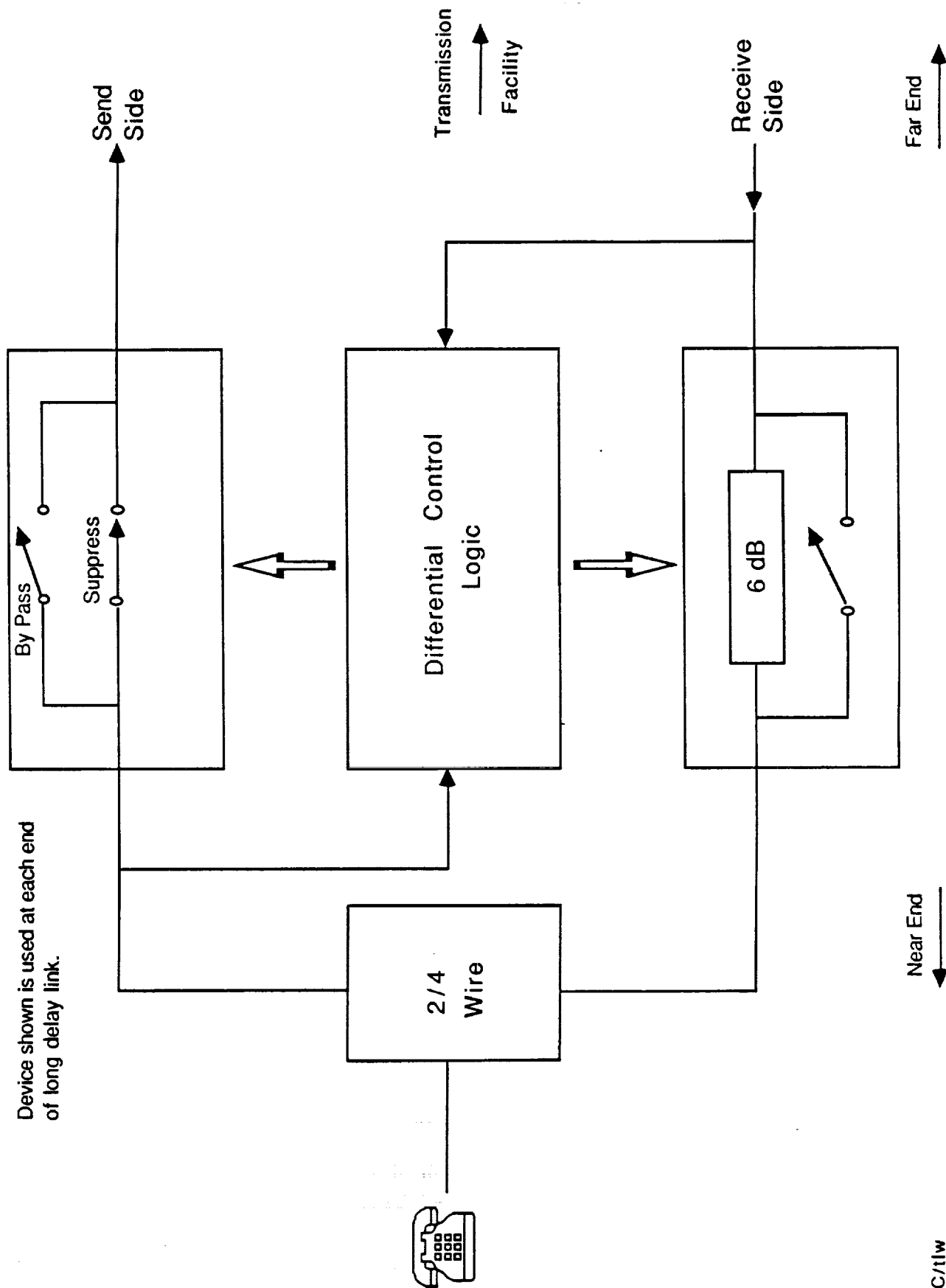
b) Echo Suppressors

O. B. Blackwell in the previously cited paper very capably described the problems of echo control. His words are as follows: "To overcome echos, it has become the practice of connecting into certain types of circuits, relay devices operated by the transmitted speech currents which render inoperative transmission in the opposite direction. In some cases delay in transmission may be an advantage in the operation of such devices. In other cases it may introduce serious difficulties. Conditions may be set up in which it is difficult for one party to interrupt the other. In other cases, portions of conversations may be locked out. If the voice-operated devices are not properly adjusted or if considerable noise is present, the devices may not function properly and speech mutilation may result".

Blackwell was, of course, referring to the echo suppressor technique that interrupts the transmission path to stop echo. The method can cause speech blocking, chopping and unwanted echo spurts if it is improperly timed. For circuits with propagation delay exceeding approximately 30 ms, echo suppressors became standard equipment on telephone trunks. In the early applications, a single echo suppressor was located near the middle of the transmission link and controlled the echo in both directions. This worked as long as the delay from the echo suppressor to either end was less than about 20 ms. When long distance submarine cable links were introduced and delays became longer, the single echo suppressor was split into two half-suppressors, one located at each end of the link. Each half suppressor stopped the echo generated from its end preventing its passage onto the transmission facility. Thus, each half-echo-suppressor protects the subscriber at the opposite end. Since all modern echo suppressors are half-echo-suppressors, the modifier "half" is usually dropped.

A modern echo suppressor<sup>[5]</sup>, shown in Figure 4, intended for cable and satellite links uses sophisticated logic to compare the signals in the two directions of transmission of the circuit and decide

Figure 4. Echo Suppressor



Device shown is used at each end of long delay link.

which customer is talking at any given instant. It places a very high loss in the send path (transmit side) to interrupt the echo when speech signal is present only on the receive path. If the near end customer starts talking simultaneously, comparator circuitry in the echo suppressor (a double-talk detector) causes the suppression to be removed (bypassed) so that he can be heard by the far end customer. Inherently it cannot perform this task perfectly. When the speech signals of both parties occur simultaneously, the suppressor rapidly inserts and removes the return path loss causing some speech to be blocked (chopping) and some echo (echo spurts) to remain. The longer the circuit delay the more annoying this condition becomes to the customers. Whenever the near end talker's signal is present, echo suppressors also switch a loss pad (typically 6 dB) into the receive side path to mitigate any echo that may slip around the echo suppressor located at the far end. This pad can become a source of degradation in mixed echo canceller/echo suppressor operation as will be described later.

Digitally implemented echo suppressors<sup>[6]</sup> have been developed that perform the complex echo suppressor control task as perfectly as can be expected and they perform better than the former analog implemented versions. Operation of these devices is critically dependent on signal levels, level balance and line noise. When these values are all within their nominal range, the echo suppressors operate well, but if they are not, then degraded performance quickly results. Even these modern digitally implemented echo suppressors inherently produce echo spurt and chopping events although to a somewhat lesser extent than the former analog implemented devices.

An example of an echo suppressor impairment that can never be completely overcome is the occurrence of "echo during double talk". This occurs when the speech from both talkers is present on the receive and send sides of the suppressor. Even though the receive side speech signal causes high attenuation to be engaged on the transmit side to stop echo, the send side speech signal is sufficient to defeat the attenuation thus permitting the passage of both the send side speech and the receive side speech (echo). Hopefully in this circumstance the echo is an average of 11 dB below the send side speech and is somewhat masked. However, if the send side talker ceases speaking while the receive side speech signal continues, in analog echo suppressors a hangover interval of 100 to 200 ms occurs before break-in can be removed during which

the echo is unmasked causing a definitive spurt of echo. This later event is called "echo after break-in". New design digital echo suppressors reduce the hangover time to about 50 ms to reduce this deficiency, none the less, it is still there. Echo cancellers totally avoid these "echo during double talk" and "echo after break-in" events.

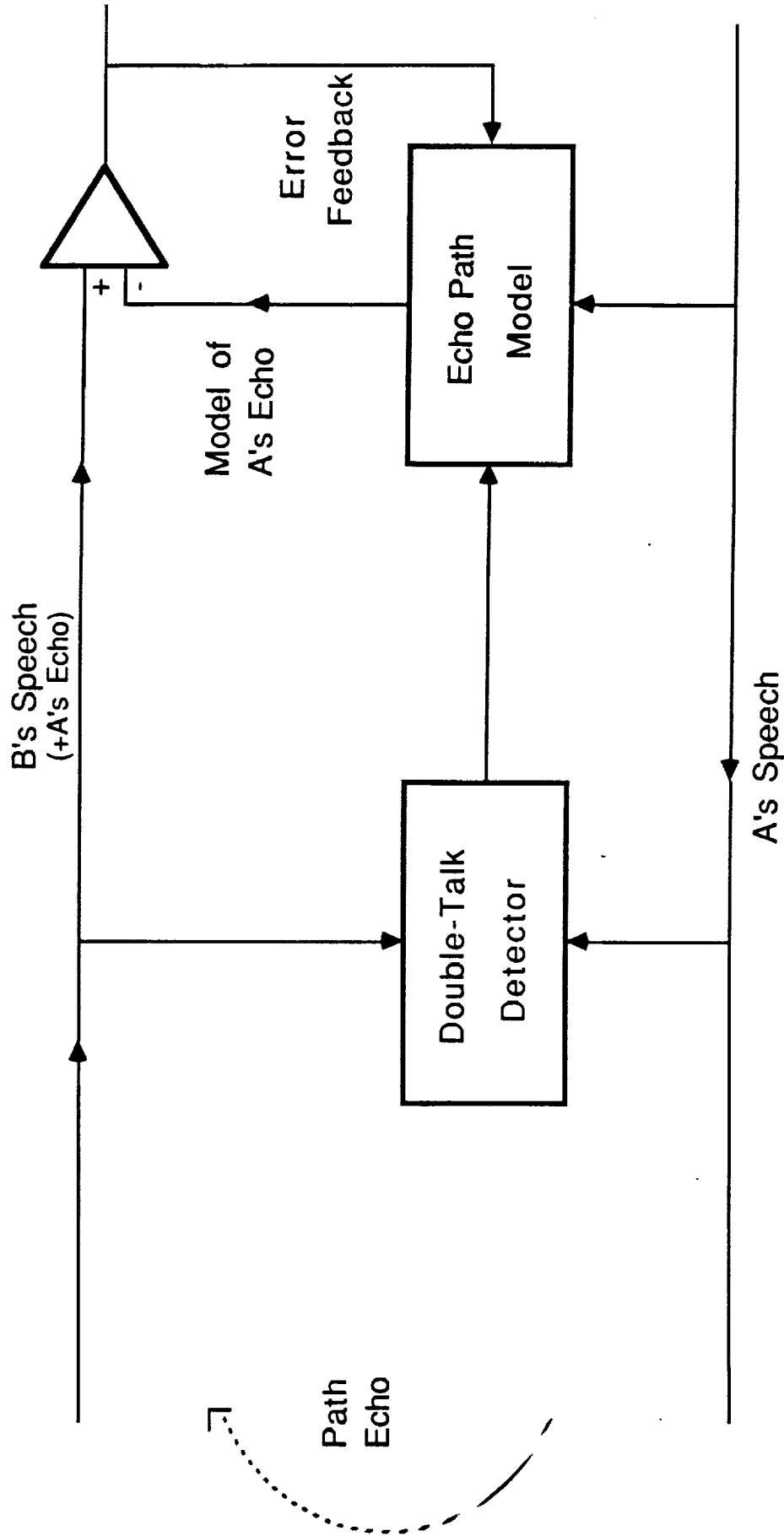
#### c) Echo Cancellers

An echo canceller, shown in Figure 5, is more sophisticated than an echo suppressor. Rather than interrupting the return path to stop echo, it creates a precise replica of the echo and subtracts it from the return path signal. This process selectively eliminates the echo. Digital signal-processing circuits that compare the signals in both directions of transmission generate the replica of the echo. Even when the return path signal simultaneously contains the sum of the near end talker's speech and the far end talker's echo, the echo is selectively removed and the near end talker's speech passes to the transmission facility unmutated. It is this inherent transparency to the wanted speech that makes the echo canceller the ideal device for echo control. The elimination of switch action used in the echo suppressor removes the causes of chopping and spurts of echo. The echo canceller was first demonstrated by computer synthesis at Bell Laboratories [7] and was first reduced to practical operational implementation by COMSAT LABS[8,9].

A canceller can achieve such effective echo control that only the delay remains to distinguish the satellite trunk from a terrestrial one. Such delay does not in itself necessarily cause difficulty. Initially the echo canceller, being a more complex device, was considerably more expensive than the echo suppressor. However, simplification of the processing algorithm by COMSAT LABS combined with LSI implementation has essentially eliminated any cost difference. Echo cancellers are now used extensively in the AT&T system for both terrestrial and satellite long-line circuits and are being adopted by many other communications systems around the world.

The CCITT has developed recommendation G.165[10] for use by telephone administrations to procure echo cancellers. Echo cancellers produce an echo return loss enhancement that augments the echo return loss already existing in the circuit. The combination is usually enough to suppress the echo to more than 37 dB below the

Figure 5. Echo Cancellation Principle



SJC/1lw



nominal return side speech signal level. During the simultaneous occurrence of return side speech, echo of this level is imperceptible. However, during silence intervals, it can be perceived as a faint whisper. Even this can be disturbing to some customers and it is necessary to eliminate the residual whisper of echo either by introducing a high fixed loss or a non-linear loss (typically a center stripper) in the return side whenever a receive side speech signal is present.

## 1.5 MAINTENANCE AND QUALITY

The excellent echo control performance of modern echo control devices can be spoiled by poor circuit maintenance. Echo suppressors and cancellers operate most effectively when the signals presented to them are within the limits specified for nominal telephone plant operation. Even the superior performance of the echo cancellers can be deteriorated when circuits are out of tolerance. Careful attention must be paid to maintaining the telephone plant parameters within the nominal limits at all points from telephone set to telephone set.

Sloppy maintenance and poor circuit engineering, especially by the less experienced private line telephone operators and even by some large country PTTs, is a major cause for unacceptable performance of telephone service over long propagation delay terrestrial and satellite links. Fortunately, the switched digital telephone systems that are currently evolving are inherently more robust in terms of maintaining operation close to system design centers. Consequently, future maintenance problems will become easier to manage and quality will improve.

### 1.5.1 Sensitivity of Echo Control To Deviations From Nominal

The signal and noise levels that occur in the forward and return directions of the telephone system are carefully selected and controlled to result in optimum performance for the customer.

#### a) Speech Signal Level Control

Speech signal level control starts and ends with the telephone set. The telephone set must be considered jointly with the

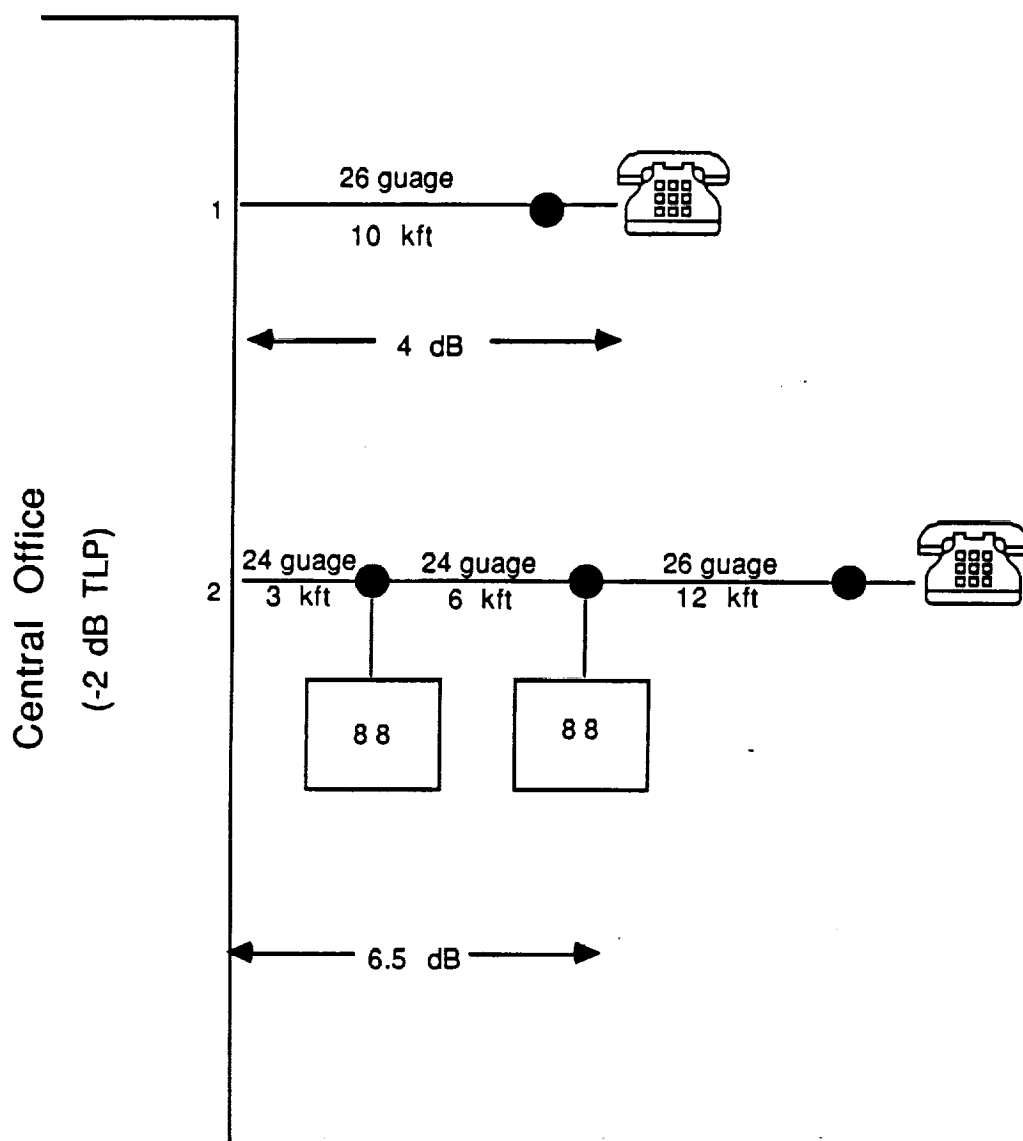
loss introduced by two wire line (also called a loop) that connects it to the central office. This two wire line supports the transmission in both directions. It terminates at the customer's end in a telephone set where a circuit, called a hybrid, splits the path into separate connections to the transmitter (mouthpiece) and receiver (earpiece). If the signal levels are just right, the customer hears a speech signal and talks at a level equivalent to that occurring in a face to face conversation with another person at a distance of 1 meter. The two wire line terminates at the other end at the telephone company's central office. This office is customarily two wire switched between other customers having a telephone with the same first three digits (central office code) and to other neighboring central offices with other first three digits. If the call is placed on a trunk going to other area codes it is converted to four wire transmission facilities by means of a hybrid and routed to a tandem switching office. It may pass through several tandem office switches before it finally terminates in the destination customers central office where it is converted back to two wire facilities and routed to the destination telephone.

The two wire lines between the central office and the customer have a length that can vary from a few thousand feet to as great as thirty thousand feet. Hence, the loop loss introduced in both the transmit and receive directions varies significantly and must be compensated. Compensation is achieved by the action of varistors contained in the telephone set that change the receive sensitivity and transmitter loss in such a way that approximately the same send and receive levels occur at the interface to the central office irrespective of the distance<sup>[4]</sup>. The varistor action is controlled by a dc line current that decreases with increasing length thereby inducing the resistance change in the varistors needed to accomplish the compensation. This design produces a specified relationship between: a) the electrical power output resulting from the acoustical signal pressure level presented to its mouth piece and b) the speech signal pressure level output at its ear piece resulting from the electrical power input. Each telephone instrument used in a network should correspond to the same specifications to assure maintenance of proper system levels. Of course, all talkers cannot be expected to exert the same vocal effort and there will be variations in the telephone instrument output level. Mouth-to-ear feedback in the form of sidetone (provided by directly coupling some of the mouthpiece signal to the earpiece) is introduced to reduce the level variations.

Within the system itself are points of reference at which certain levels are expected. There is a reference point called the 0 dB transmission level point, OTLP, assumed to exist within the telephone system, at which the expected long term average signal power level is -22 to -25 dBm. The electrical transmit and receive signals occurring at the central office end of the loops that correspond the expected mouth and ear piece sound pressure levels at the telephone set are both at levels -2 dB (alternatively -3 dB) relative to the OTLP. Two local loop examples are shown in Figure 6. The local loop losses are nominally between 4 and 6.5 dB. Even though the loop losses differ as a function of line length, the telephone sets, through the use of varactors interacting with the direct current flowing in the loop, compensate the transmit and receive side signal levels to produce the nominal central office levels. Levels appearing on the receive and transmit sides of four wire trunk transmission facilities in the Bell System are at -16 and +7 dB relative to OTLP. This is shown in Figure 7. When private Interlata Carriers (ICs) interface with a Bell Operating Company (BOC) to gain access to their customers they must present to the system the correct levels to achieve good service. If for some reason the specified expected interface levels are not maintained, the system will be out of tolerance with send and/or receive levels too high and/or too low. Prior to the equal access rulings, "out-of-tolerance" conditions were frequently encountered by independent carriers interfacing into the Bell Systems.

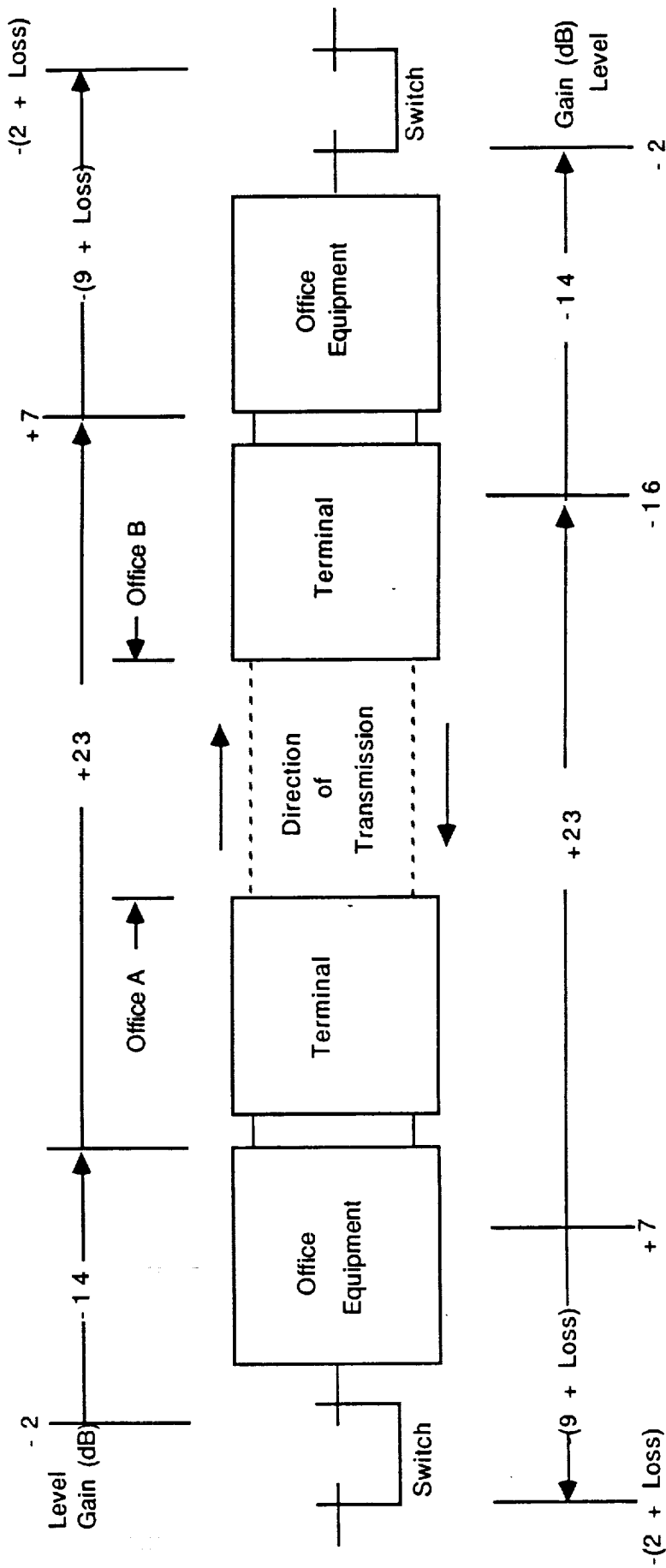
Such conditions can result in degradation of echo control performance. For example, a difference of +6 dB between the expected return and receive side levels will cause the echo return loss to be 6 dB less than it should be. This will increase the echo level by 6 dB, degrading the performance of echo cancellers and echo suppressors and delivering a less acceptable service to the customer. Signal level activated devices such as the conventional echo suppressors which have signal level threshold detectors to activate critical functions will effectively have these levels shifted by departures from the nominal levels increasing the likelihood of impairments due to echo spurts or speech signal chops. Both laboratory and operational field tests have demonstrated that such events will be more detrimental on long propagation links. In fact, it will be shown later that when such impairments are eliminated the quality perceived by customers differs little between short and long propagation delay circuits.

## Figure 6. Two Example Loops



Note: 88 denotes an 88mH loading coil.

Figure 7. Transmission Levels: 4-wire  
Trunk with 2-wire Switching



## b) Noise Levels

Excessive noise in the system due to equipment malfunction or transmission interference will also degrade the performance of echo control equipment. Noise levels sufficient to impair operation should not normally occur provided the facilities are properly maintained and the performance margins on radio links are within the recommended bounds. Nominal noise levels on international and long distance links should normally be -52.5 dB below 1 mw measured at the OTLP and is even lower on national links. Nominal speech power during active speech is 25 dB above the noise, which is more than sufficient to guarantee good performance of the speech power activated switches used in the echo suppressors. Probably the local loop plant with its two wire lines connecting users telephones to the local telco office are a prime source of noise and level problems.

The influence of noise on echo suppressor operation is to change the effective receive side signal level at which the return side suppression is invoked and the difference threshold between return and send signal levels at which break in is invoked. For example, high receive side noise reduces the speech power level at which suppression is invoked and if high enough, it can hold the echo suppressor in the suppression condition permitting only high transmit side speech segments sufficient to invoke break-in to pass. This causes severe chopping of the return speech much to the consternation of the far end subscriber. Also high noise on the transmit side can constantly engage the break-in function, defeating the suppression and causing continuous echo.

## c) Preservice, Acceptance and Maintenance

Telephone system performance depends critically on the attention paid to preservice, acceptance and continuing maintenance to assure that performance objectives are initially met and continue to be met. Preservice, acceptance, maintenance, and immediate action limits are based on the performance obtainable with existing equipment and operating procedures. Preservice limits reflect the capabilities of a service when it is properly installed and adjusted. They include tests of transmission parameters that generally remain stable over the lifetime of the equipment. Acceptance limits are similar to preservice limits and represent a maximum or range of a parameter that is allowed where cooperative tests are conducted

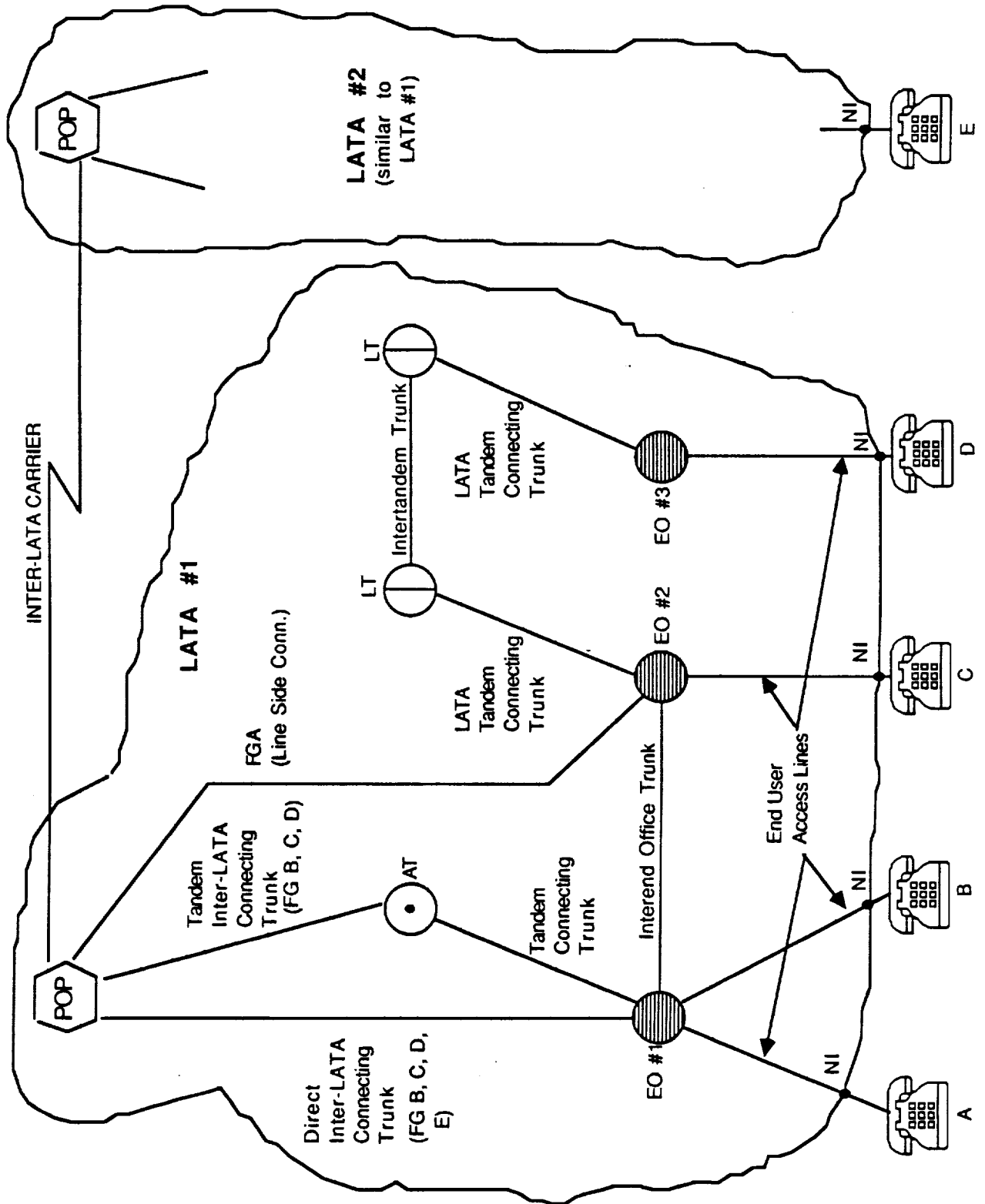
with a customer prior to turnup. Acceptance limits may include some margin with respect to the corresponding preservice limits to allow for difference in test equipment, methods, and time of measurement. Maintenance limits are thresholds beyond which corrective action should be scheduled. Immediate action limits are thresholds beyond which transmission is deemed unsatisfactory and immediate corrective action is indicated.

## 1.6 EQUAL ACCESS

As a consequence of the Computer II decision, the Bell System was ordered to allow access to independent carriers (ICs). This created the impetus for the establishment of competitive long distance telephone carriers who used the local telco facilities to reach subscribers. However, there was no requirement that the access provided had to be the same as that provided to AT&T long-lines. This situation prevailed until the divestiture of the Bell Telephone Company in the US, ordered by the Courts in the Modified Final Judgement (MFJ) in 1982, and implemented on January 1, 1984. The traditional concept of end-to-end service provided by a single company had to be altered. The old Bell Telephone Company has been broken into the seven Bell Operating Companies (BOCs) and the AT&T Company. The BOCs control access to the telephone subscribers, while the AT&T Company provides the long-lines interconnections.

To implement the divestiture, services have been classified as intra-exchange (BOC), access (BOC), and inter-exchange (IC)<sup>[11]</sup>. The Bell System portion of the network has been divided to reflect this segmentation of responsibility. The BOCs have divided the territory they serve into areas known as Local Access and Transport Areas (LATAs). Calls originating and terminating in the same LATA (i.e., intra-LATA calls) are typically handled, as in the past, by the telephone company that serves that LATA. However, calls that originate and terminate in different LATAs (i.e., inter-LATA calls) are transported between LATAs by a carrier referred to as an Inter-LATA Carrier (IC). Intra- and inter-LATA switched access arrangements are shown in Figure 8. The MFJ imposes similar requirements on all of the other independent telephone companies operating in the US. The quality of the access prior to and following the MFJ is also significantly different as discussed below.

FIGURE 8. SWITCHED LATA ACCESS



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### 1.6.1 Access Prior To The MFJ

Prior to the Bell divestiture (MFJ), independent ICs were not given the same access to the subscribers controlled by the BOCs in terms of services as was AT&T. The services referred to include network control signaling, answer supervision, automatic calling number identification, carrier access codes, directory services, testing and maintenance of facilities, and the provision of billing data. The disadvantaged independent ICs, none the less, attempted to provide their services to customers who would subscribe. The same situation applied to private companies who wanted to establish their own private corporate telephone systems. This situation not only created a complicated procedure for dialing numbers, establishing supervision and signaling, and billing the calls but also created a difficult problem for testing and maintaining the interfaces between the IC and Bell facilities. Neither the BOCs nor AT&T, who had the skills and experience, were responsible for testing and maintenance and the independent ICs were frequently presented with out-of-tolerance conditions. Consequently, the quality of the service provided to subscribers by the independent ICs and private corporate networks suffered immensely.

This was the situation that prevailed during the early days of divestiture when many independent ICs and private companies were exploring the use of satellite links for both public and private networks. It created major service quality problems for those ICs and private companies that attempted to operate independent networks, especially when satellite links were used, not fully understanding the extent of testing and maintenance required to achieve the performance objectives needed to assure subscriber acceptance. It is not surprising that independent IC and private network subscriber complaints about service quality were all too frequent in this period. When some independent ICs established their own test and maintenance program, as did Satellite Business Systems, the service quality improved markedly and frequently was rated as equivalent to that of the highest quality terrestrial links. However, this came at the added expense of test and maintenance and few ICs did anything to correct the situation.

The introduction of satellite links at a time when the testing and maintenance was uncontrolled, resulting in inferior quality and unacceptable service to subscribers, may have soured many private line networks and independent ICs on the use of

satellite links for domestic telephony in the US. The number of subscriber complaints that have been attributed to satellite links in the US domestic service in this pre MFJ period, when the professional testing and maintenance practices of the Bell System and AT&T were not available to the majority of the independent ICs, far exceeds the experience encountered in the international satellite systems which operate fully within the jurisdiction of AT&T.

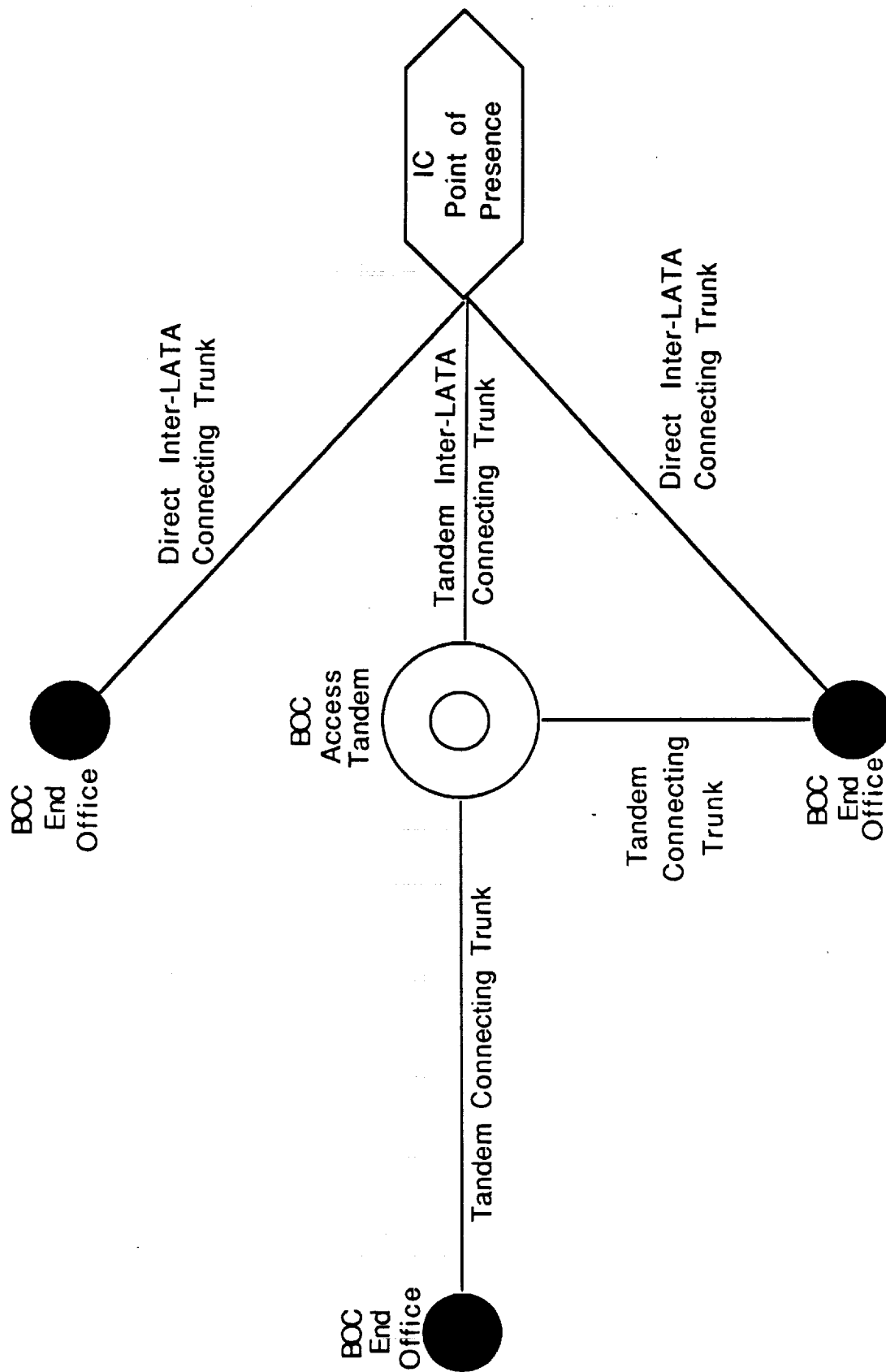
#### 1.6.2 Access After The MFJ

Equal access has now greatly improved the circumstances for the independent IC and private line network provider. The Modification Of Final Judgement (MFJ) requires that all ICs be given equal access to BOC LATAs. That is, all carriers must be provided services that are equal in type, quality, and price to those provided AT&T. LATA access services connect ICs to their customers located within a LATA and are used in the origination and termination of inter-LATA and, in states where it is authorized, intra-LATA telecommunications. Generally, each IC desiring LATA access services must establish at least one Point Of Presence (POP) in each LATA it wishes to serve as shown in Figure 9. The POP serves as the concentration and distribution point for the services of that IC and is the location to which the BOC provides LATA access. The MFJ specified the type of services that the BOCs would be allowed to provide after divestiture. They include exchange (LATA) access, exchange (intra-LATA), and information access. These services, which guarantee the connection quality all the way from the POP to the subscriber's termination, must be available on a tariffed, unbundled basis and must be provided to all carriers and customers on an equal basis. The availability of equal access to the independent ICs will enhance quality and improve performance of satellite links. It is regrettable that the peak of satellite circuit use in the US occurred before the equal access provisions ordered by the MFJ came into force.

#### 1.7 SUBJECTIVE REACTION TO ECHO AND PROPAGATION DELAY

The difference in telephone communications quality as delivered by satellite links with long propagation delay compared to that delivered by terrestrial links with short propagation delay has been a subject of debate and investigation for two decades.

Figure 9. Switched Access Configuration



Propagation delay and echo are the issues. It is generally accepted that echo is extremely detrimental to short and long propagation delay telephone links and needs to be eliminated. Also results of experiments generally show that subscriber perceived impairments attending echo free long propagation delay single hop geostationary satellite links are very small. Real operational systems on the other hand in which echo must be eliminated by echo control devices always exhibit increased impairments which are closely related to the effectiveness of the echo control devices. Both echo suppressors and echo cancellers are in use today and the latter definitely have proven to be far superior on the long propagation delay satellite links. Numerous theoretical, laboratory and field studies and investigations have been performed and many of these are discussed in the following section. The discussion that follows is divided into:

- 1) Human factors consideration of speech interaction,
- 2) Subjective reaction to delay without echo
- 3) Subjective reaction to delay with echo
- 4) Field tests on live traffic.

#### 1.7.1 Speech Interaction Among Humans

Face to face speech interaction among humans is a process which is regulated by auditory and visual cues. Turn-taking during conversation is facilitated by components of the speech itself, while additional relevant information is provided by some body movements. In an interactive environment, communications systems with delay may modify the temporal interaction patterns of conversation and consequently interfere with its flow and in extreme cases with the intended information content of speech messages<sup>[12]</sup>.

The exchange of the talking role in telephone conversation, referred to as "turn-yielding", may be signaled by five possible auditory cues<sup>[13]</sup> : (1) intonation, or a change in voice pitch at particular syntactic locations, (2) drawl on the final syllable or on the stressed syllable of a terminal clause, (3) stereotyped expressions such as "but uh" or "you know", (4) a drop in voice pitch and/or loudness in conjunction with a stereotyped expression, (5) syntax;

specifically, the completion of a clause involving a subject-predicate combination.

Other signals identified<sup>[14]</sup>, which might be called "turn-taking", indicate that a listener wishes to shift to the talker state. Prior to expressing a turn-taking signal, he may or may not have been participating in back-channel behavior consisting of small units of speech such as "m-hm" or "yeah", but which do not pretend to claim the floor. Typical "turn-taking" signals are audible inhalation, and paralinguistic overloudness.

Talker switching times refer to the intervals between reversal of talking between dyads (pairs of conversants). The distribution of talker switching times has been shown to have a modal value around 200 to 300 msec<sup>[15]</sup>. Such short switching times imply that responses to turn-yielding signals occur with short delay following emission of the signals. When a turn-yielding signal is given, the speaker has the intention of yielding the floor to someone else. If the implicit offer is not accepted immediately, it may be withdrawn and the speaker may continue. A tardy acceptance of the offer of the floor in excess of 200 to 300 msec, might then result in confusion due to simultaneous speaking.

Such tardiness can result from conditions imposed by telephone circuits with long propagation delay. The round trip delay can be 100 ms on trans-Atlantic submarine circuits, 160 ms on Trans-Pacific submarine cable circuits, 240 ms on terrestrial circuits from Europe to the Orient via North America, and 600 ms on geostationary orbit satellite circuits. If the turn-yielding signal is delayed by amounts in excess of 200 to 300 ms, the delay between emission of the signal and the response to that signal is significantly more than that normally expected. A talker unaware of the physical delay due to the circuit, may continue speaking following a period of high probability of a response, resulting in simultaneous speaking. Similarly, delay of a speech signal can also result in confusion if both parties emit such a signal, and the two signals are separated by less than the delay time of the circuit. With short round trip delay, a speech signal can be inhibited if a similar signal is received from someone else. With long round trip delay, a speech signal may be emitted before receiving the signal from the far end possibly causing confusion as to who possesses the floor.

The effect of delay on conversation interaction should be expected to be less when the conversants speak slowly rather than quickly. Slow speech, resulting in longer switching pauses, would allow turn-yielding signals and speaker-state signals to be received before utterances are initiated at inappropriate times.

#### 1.7.2 Subjective Reaction To Delay Without Echo

Numerous subjective evaluations have demonstrated that round trip delays of as much as 600 (single hop satellite) and 1200 ms (double hop satellite) on echo free circuits remain almost unnoticed<sup>[16,17]</sup> in a telephone conversation. However, there is evidence that delay does affect overall conversational dynamics. These results imply that even though people may not notice a change in the circuit delay, their speaking patterns may still undergo changes of which they are unaware. It is possible for people to adapt themselves to longer delays (as evident by intercontinental telephony via satellite circuits) and delays up to several hundred milliseconds appear to go unnoticed by most users.

##### 1) Kraus and Bricker

Krauss and Bricker<sup>[16]</sup> investigated the effect of delay in voice circuits free of echo sources and echo suppressors. College students were requested to perform, in pairs, a task which required the transfer of information from a "sender" to a "receiver". Round trip delays of 50, 600 and 1800 msec were employed. The objective results indicated no differential effect on the interaction between the 50 and 600 ms delays. However, the 1800 msec delay (corresponding to triple satellite hop) appeared to increase the number of words used by the sender relative to both of the shorter delays. But since no effect was noted on the number of utterances, it was concluded that the long delay tended to increase the length of the sender's utterances. No effect on the receiver's behavior was noted. The subjective results indicated that subjects in the 1800 msec delay condition, regarded their partners as significantly less attentive. Such a perception might be considered the result of longer response latencies forced by the long round trip delay.

##### 2) Brady

Brady<sup>[17]</sup> performed an extensive analysis of vocal interaction between dyads (pairs of conversants) using echo-free

telephone circuits with round trip delays of 0, 600 and 1200 msec. Three kinds of objective measurements were taken: (a) the first five minutes of each session was evaluated for the presence of confusion which was defined as a reaction to simultaneous speech (e.g. "What?"), or self-generated repeat, or a sudden halt in the middle of an utterance, (b) an objective loudness measurement was taken from the first five minutes of speech and (c) an automated on-off speech pattern analysis was performed over the entire duration of each experimental condition. The subjects were not aware of the delay conditions. The number of confusions as measured by observers increased significantly at 600 ms compared to 0 ms delay but did not increase any more at 1200 ms. Speech loudness was not influenced by delay. The occurrences of simultaneous speech and mutual silences increased from 600 ms to 1200 ms: however, no observations were made for these events at 0 ms delay. The subjective reaction was obtained by interviewing the subjects separately following each experimental session. The subjects were asked if they had noticed anything unusual about the circuit. None of the subjects' opinions reflected any awareness of the existence of the delays. Two pairs in the 1200 msec delay condition said that confusion had occurred but the problem was not attributed to any circuit characteristic.

3) Pavlick, Anderson, Chamberlin, Byrne and Mou

Pavlick, Anderson, et. al. of the Department of Psychology, University of Maryland performed a study to examine propagation delays over a range from 0 to 999 ms introduced into a laboratory telephone system<sup>[18]</sup>. For the assessment of acceptability, quality rating scales developed at the Naval Research Laboratory by Schmidt-Nielsen and S. S. Everett<sup>[19]</sup> for studies of communicability were used. The rating scales were completed by each speaker at the end of each conversation. Each conversation involved two talkers (a dyad) conversing about content specified by the task instructions. Thirty-two pairs of students participated in the study. Data were acceptable for twenty-seven pairs.

The apparatus used in the experiment simulated long propagation delay encountered on satellite telephone links. The main apparatus included three ITT Model 2500 telephones (in isolated rooms) with doors separated by 4.4 meters and a monitor (in the room between) connected to a long propagation circuit simulator. A digital delay line allowed the introduction of delays ranging from 0

to 999 msec in each direction of the telephone system used for conversations.

Participants were introduced to each other and informed of the particular tasks to be performed. They were told that the purpose of the experiment was to assess the communications quality of the particular systems tested, i.e., delay levels were referred to as systems. The dyad was also warned that not all systems were considered to be low quality. In fact, some systems tested would be so called "perfect systems", that is they would not differ from normal telephone conversation (delays = 50-85 msec). Conversation was stimulated by assigning the participants various tasks.

Following the conversation, each of the participants answered a questionnaire consisting of five items. Four of these items involved rating the effort required to communicate, the naturalness of voice quality, the need to speak carefully and the overall acceptability of the system. The items were to be rated on a 7 point scale with 7 for excellent, 1 for unacceptable, and 4 as moderate. The fifth question addressed the value of the particular system being tested. More specifically, it asked participants how much they would pay for such a system given a ten dollar baseline amount for AT&T services.

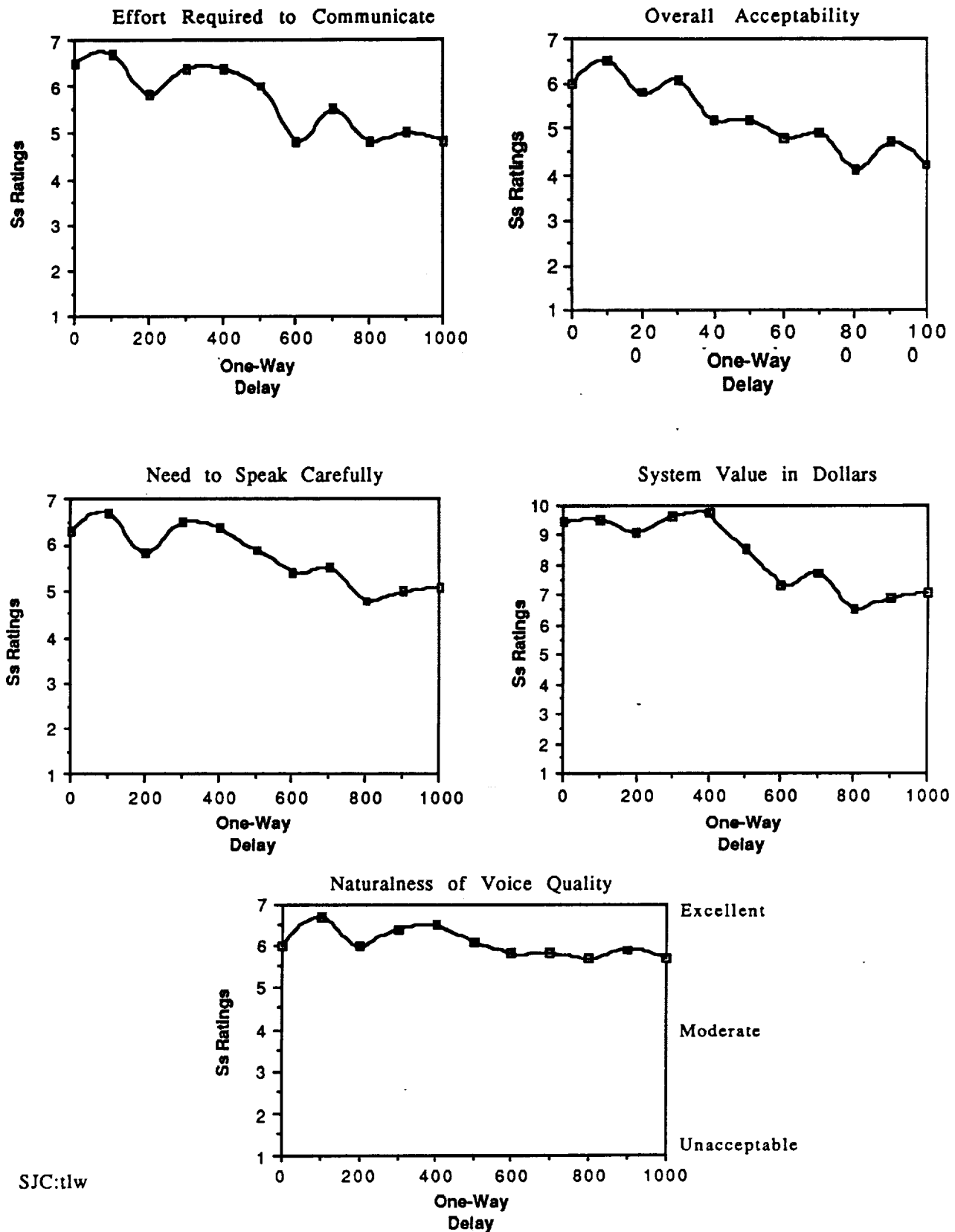
Graphs of the averages of the five rating functions as a function of one-way propagation delay are given in Figure 10. The rating data demonstrated that subject pairs lowered their ratings as delay increased. These decreases in many cases were found to be statistically significant even though the average ratings across subjects and tasks were never below a value of 4, the middle of the scale or "moderate" compared to excellent and unacceptable.

The subject pairs were notably consistent in rating the 60 msec condition as highest both at the beginning of the study and as the last task. Given the absence of within subject differences across these delays and the additional factors mentioned, it is necessary to withhold interpretation of the apparent decrease in subjects judgments at 200 msec.

For all rating functions, the values achieved at a propagation delay of 300 ms corresponding to a single hop satellite link were only slightly less than those observed for the 60 ms



Figure 10. Quality Rating Scales



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conditions. The values for 600 ms corresponding to a double hop satellite link were considerably lower.

These results are consistent with those obtained in the previous studies discussed in long propagation delay on echo free single hop satellite circuits does not constitute a serious impediment to conversation.

### 1.7.3 Subjective Reaction To Delay With Echo

Laboratory tests performed by Standard Telephone Labs (STL) in the UK, KDD of Japan, and NEC of Japan which investigated the reaction of subjects to delay when various amounts of echo were injected are summarized in the following.

#### 1) Standard Telephone Labs (STL)

Subjective performance of simulated long delay telephone communications was performed by STL in Harlow, Essex, UK under INTELSAT sponsorship<sup>[20]</sup>. It measured and analyzed the mean opinion scores and percentage difficulty observed by subjects conversing over a simulated long delay telephone link in which the delay (mean one-way propagation time), echo return loss, and echo path frequency characteristic were varied. The delay varied between 50 and 600 milliseconds, the echo return loss between 15 dB and 50 dB, and the echo path frequency characteristic was either flat or shaped (in which case the echo level increased with frequency). Only the results for the flat characteristic are discussed here.

The sensitivity of a telephone talker to echo as a function of the path delay was investigated to assess how much echo return loss was required to achieve acceptable performance over long distance links. Echo return loss values of 15, 25, 31, 37 and 50 dB were tested. The experiment also provided valuable information on subscriber reaction to single hop satellite links. A substantial effort was made to place the subject pairs involved in the tests in the setting of an actual telephone conversation. Conversation was stimulated by presenting the subjects with problem solving tasks.

When a conversation was completed, the subjects filled out an assessment form that asked them to rank the service quality in terms of the words excellent, good, fair, poor or bad. These were

given numerical weights of 4,3,2,1,0 respectively which were averaged to produce a mean opinion score (MOS). Thus, an MOS of 3.0 corresponds to an average ranking of good. The subscriber subjects were also asked if they had difficulty and if they said yes, they were to identify the cause of the difficulty from a list of possible difficulties.

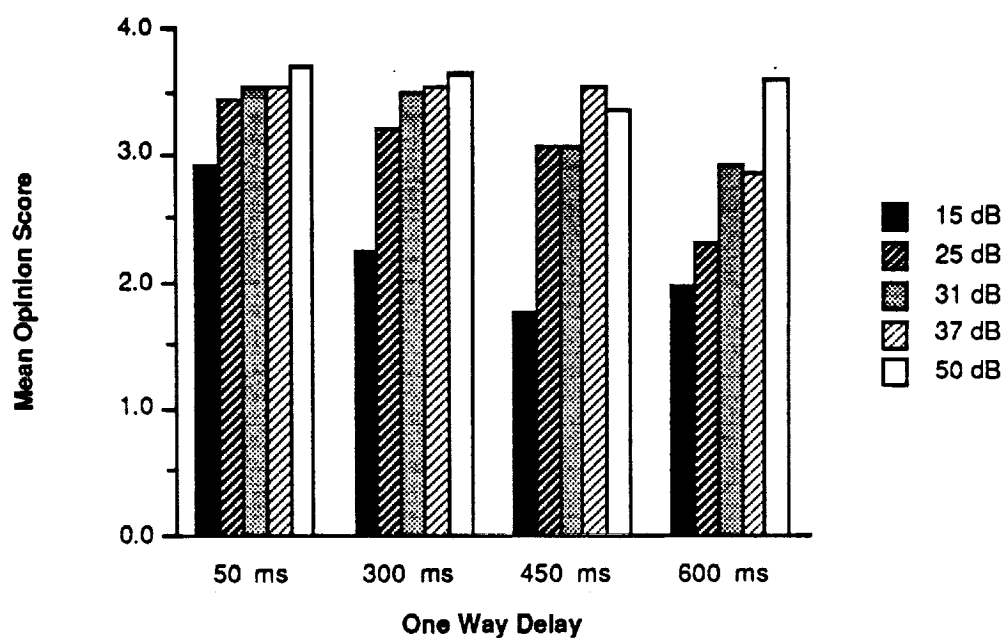
Table 1 lists the mean opinion scores (MOS) obtained for the different delay and echo conditions. The 95% confidence limits for each MOS are equal to  $\pm 0.36$ . The MOS values are plotted as a function of echo return loss for various values of one-way delay in Figure 11. It is evident that for zero delay, the variations in echo return loss values would have a negligible effect on the MOS. Therefore, it is reasonable to expect the curves to tend towards a common MOS for low values of delay as is evident in the figure.

TABLE 1  
MEAN OPINION SCORE VERSUS ECHO PATH DELAY  
FOR VARIOUS VALUES OF ECHO RETURN LOSS

ONE WAY DELAY	<u>ECHO RETURN LOSS</u>				
	15dB	25dB	31dB	37dB	50dB
50 ms	2.90	3.45	3.55	3.55	3.70
300 ms	1.75	3.05	3.05	3.55	3.35
450 ms	2.10	2.25	3.50	3.30	3.30
600 ms	1.90	2.70	2.85	2.90	3.45

Table 2 lists the percentage of subjects who reported difficulty for the different delay and echo conditions. Each point represents only 20 observations resulting in rather wide confidence limits. For example, the 95% confidence limits on a percentage difficulty score of 30% are 12% and 54%. The results from Table 1 are also plotted in Figure 12.

**Figure 11. Mean Opinion Score as a Function of Echo Return Loss and One-Way Delay**



**Figure 12. Percent Difficulty as a Function of Echo Return Loss and One-Way Delay**

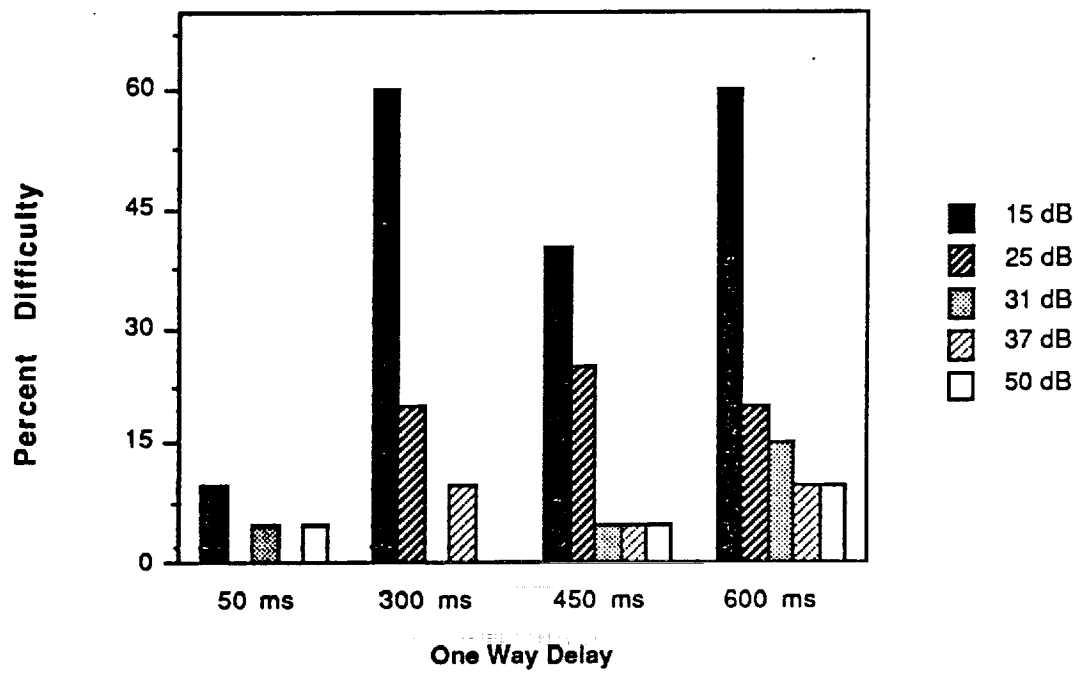


TABLE 2  
PERCENTAGE DIFFICULTY SCORES  
ECHO RETURN LOSS

ONE WAY DELAY	15dB	25dB	31dB	37dB	50dB
50 ms	10	0	5	0	5
300 ms	60	20	0	10	0
450 ms	40	25	5	5	5
600 ms	60	20	15	10	10

Both the MOS and percent difficulty results obtained from the experiments described above indicate improved subjective performance at all propagation delay values with increased echo return loss (equivalent to decreased echo level relative to the wanted speech). One important conclusion is that echo is eliminated as a source of impairment for echo return loss in excess of 37 dB. This was important information for the design of echo cancellers. A second conclusion was that for the high echo return loss (faint echo), the mean opinion score increased to about 3.5 and the percent difficulty to less than 10% for single hop satellite delay and for the double hop satellite delay the values did not significantly worsen. An analysis of the causes of difficulty showed that there were 157 reports of difficulty out of a possible 800. 73% of these identified echo as the cause while only 5% gave delay as the cause, indicating that echo is a far greater impediment than propagation delay. It is also interesting to note that MOS and percent difficulty for circuits with only 50 ms of delay and an echo return loss of 15 dB were worse than those for single and even double satellite hop delays with the high echo return losses.

## 2) KDD

A subjective evaluation experiment very similar to that performed by STL as discussed above was also performed by KDD of Japan under INTELSAT sponsorship<sup>[21]</sup>. It differed slightly in the values of echo return loss used but used the same values of propagation delay. Similar concepts for creation of a telephone call

environment and conversation stimulation were used. The number of subject exposures included in the statistical assessments and simulation of the telephone circuits with metered amounts of echo were used. Of course, a strong difference existed in that all subjects were native Japanese speaking and were influenced by their cultural background and their interpretation of the meanings of their lingual equivalents of the rating terms excellent, good, fair, poor, unacceptable and difficulty used in the evaluations. Thus, it is not surprising that some overall bias shifts were observed in the scores as compared to those obtained by STL for similar circumstances.

The results obtained for the MOS are given in Table 3, for percent difficulty in Table 4, and for the percent unacceptable in Table 5. The following observations are appropriate.

TABLE 3

MEAN OPINION SCORE VERSUS ECHO PATH DELAY  
FOR VARIOUS VALUES OF ECHO RETURN LOSS (KDD)

		<u>ECHO RETURN LOSS</u>				
ONE WAY DELAY		21dB	31dB	37dB	43dB	56dB
50 ms		2.079	2.276	2.398	2.306	2.364
300 ms		1.777	2.133	2.256	2.306	2.325
450 ms		1.589	1.992	2.132	2.198	2.348
600 ms		1.690	1.883	2.029	2.224	2.250

TABLE 4  
PERCENTAGE DIFFICULTY SCORES (KDD)

ECHO RETURN LOSS

ONE WAY DELAY	21dB	31dB	37dB	43dB	56dB
50 ms	13.693	5.858	6.224	7.660	7.531
300 ms	31.405	12.500	8.264	8.678	5.833
450 ms	39.834	15.417	11.489	9.504	7.377
600 ms	40.083	21.667	13.278	9.283	7.759

TABLE 5  
PERCENTAGE UNACCEPTABILITY SCORES (KDD)

ECHO RETURN LOSS

ONE WAY DELAY	21dB	31dB	37dB	43dB	56dB
50 ms	20	10	8	7	7
300 ms	36	15	10	11	9
450 ms	46	20	13	15	9
600 ms	42	26	18	11	10

1. For low echo return loss (loud echo) the values of MOS, percent difficulty and percent unacceptable all degrade in unison as propagation delay increases.
2. For short and long propagation delays, decreasing echo return loss ( increasing echo loudness) consistently degrades performance.
3. For high echo return loss (very very faint echo), increasing propagation delay results in only small increase in degradation.



These results, as well as those obtained by STL, show that the occurrence of echo is far more degrading to service than is propagation delay. The differences in MOS, percent difficulty and percent unacceptability between 50 ms and 300 ms propagation delay for a constant echo return loss of 56 dB are very small: MOS going from 2.36 to 2.35, percent difficulty from 7.3% to 5.8% and percent unacceptable from 7% to 9%. The differences in the same measures between 21 to 56 dB of echo return loss for constant 300 ms propagation delay are large: MOS going from 1.77 to 2.33, percent difficulty from 31.5% to 5.8% and percent unacceptable from 36% to 9%. These results suggest that appropriate control of echo virtually eliminates the difference in performance between cable circuits and satellite circuits over distances across the oceans and the continents.

### 3) NEC

Muira, Sato and Nagata of Nippon Electric Company<sup>[22]</sup> in 1966 reported experimental work on a comparison of the performance of two echo suppressors and a very early version of an echo canceller called a blockless echo suppressor. Subjective performance of these were evaluated over simulated telephone circuits having one-way delay without echo from 100 to 600 ms. One echo suppressor was simply a voice activated send side switch that closed when the difference between the send side and receive side voice signal levels exceeded a selected threshold level. The second echo suppressor was equipped with a send side switch that opened whenever the receive side signal exceeded a selected threshold and a bypass switch that closed when the difference between the send and receive signals exceeded a selected threshold. In the case of the blockless echo suppressor, a replica of the echo was calculated by convolving the receive side signal with the impulse response of the echo path and this was subtracted from the send side signal to cancel the echo while not impeding the transmission of the wanted send side speech signal. This action created an additional echo return loss enhancement of 20 dB. Because no switching was used, the method was referred to as "blockless" echo suppression. The impulse response was obtained by sending a special signal down the line from the location of the blockless echo suppressor to the terminating end. Modern echo cancellers use the receive side speech signal to continuously calculate the impulse response and achieve echo return loss enhancements of 25 to 30 dB.

Evaluations were performed to reveal the relative subjectively perceived degradation experienced in conversation over long propagation circuits for each of the echo control devices described above. The results were expressed in terms of the categories "not perceptible", "perceptible but not objectionable" and "definitely objectionable". The results are plotted in the graphs shown in Figure 13 for simulated circuit echo return losses of 5, 11, and 17 dB. Curves marked A are for a reference echo free condition, BL for the blockless echo suppressor, N for the echo suppressor with the send side break in function and B for the echo suppressor without the send side break in function.

The blockless echo suppressor results are very near to those of echo free operation for all values of echo return loss. For single hop satellite delay (300 ms one-way delay) the performance degradation with the blockless echo suppressor was always rated as "not perceptible". Even for the double hop delay (600 ms one-way delay), the degradation was on the border of "definitely perceptible but not objectionable". Also, the difference between the performance at short delays of 100 ms, typical of long terrestrial cable circuits, and the single hop satellite circuit was greatly reduced when the blockless echo suppressor was used.

Results for the echo suppressors are considerably inferior especially for the longer propagation delays. Both types of echo suppressors at the single hop delay conditions remained in the region bordering definitely objectionable. This is attributed to the occurrence of echo spurts and speech mutilation due to chopping.

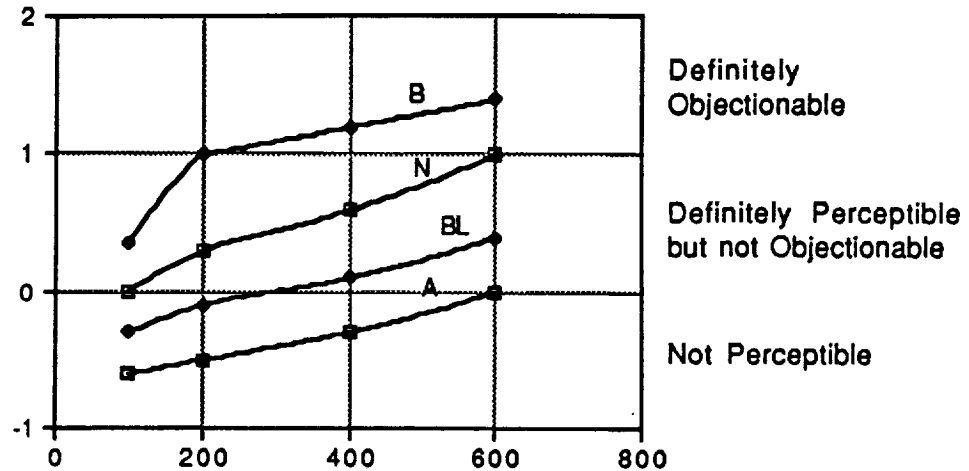
#### 1.7.4 Conclusions Relating to Human Factors and Laboratory Studies

Results of human factors and subjective reaction laboratory studies just described indicate that echo by far is the cause of difficulty in long propagation delay telephony and that the switching nuances attending the echo elimination operation of the widely used echo suppressors frequently leave the speech signal mutilated. Either of these echo related impairments are exacerbated by long propagation delay. However, when echo is eliminated and propagation delay is the only remaining factor, the difference in the subjective opinion of the performance of long and short propagation delay circuits is virtually insignificant. In the next section, the

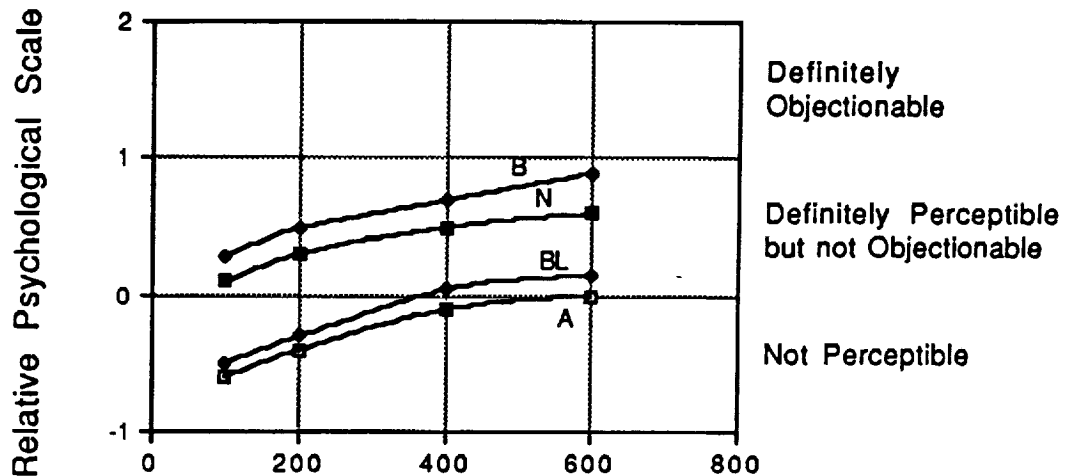
Figure 13. Results of Subjective Evaluation of the Three Echo Suppressors

- A = Echo Free
- B = Echo Suppressor (send switch)
- N = Echo Suppressor (break-in)
- BL = Blockless Echo Suppressor

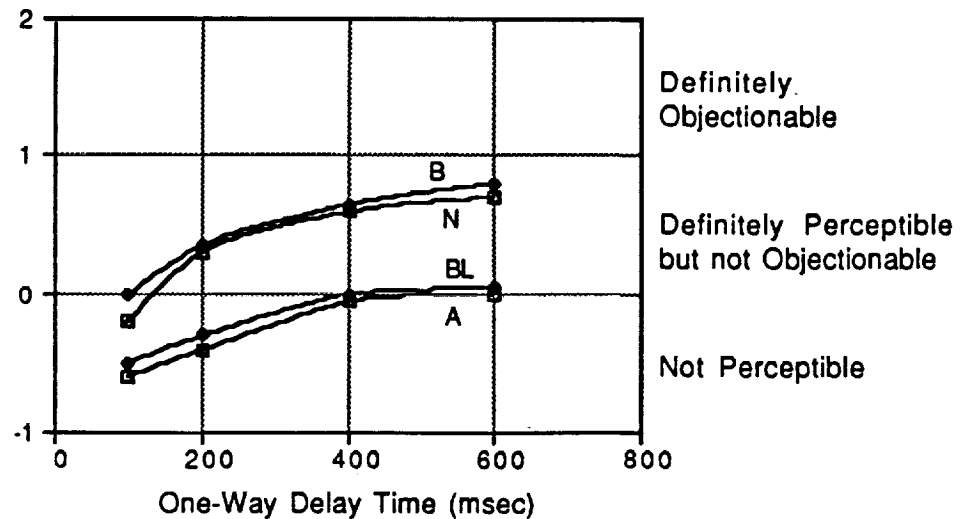
Return  
Loss 5dB



Return  
Loss 11dB



Return  
Loss 17dB



results of field tests designed to gather the opinions of subscribers using operational long distance facilities over terrestrial and satellite links equipped with echo suppressors and echo cancellers will be presented. This will prove an opportunity to see how well the implications of the laboratory tests hold up in the real world.

## 1.8 OPERATIONAL TELEPHONE CIRCUIT FIELD TESTS

Human factors arguments presented in the foregoing, indicate that telephone system subscribers may be influenced by propagation delay for round trip delays in excess of a few hundred ms. However, laboratory experiments performed largely on subjects in their 20's and 30's indicate that, unless there are mitigating circumstances that cause the speech signal to be mutilated, the largest percentage of those tested indicate no sensitivity to single hop satellite delay and exhibit almost negligible increase in sensitivity to double hop delay.

In the following, reports are given on field tests designed to assess subscriber opinion on circuit quality using operational long distance telephone circuits in domestic US, Canadian and international Atlantic Ocean applications. The field tests reported were conducted by: INTELSAT and COMSAT on international circuits, AT&T on US domestic circuits, Bell-Northern Research on Canadian domestic circuits, and COMSAT on the circuits of a US private telephone network.

### 1.8.1 INTELSAT/COMSAT Echo Canceller Field Trials

#### 1.8.1.1 Test Organization

Echo cancellers developed by COMSAT Laboratories and others by INTELSAT under contract with NEC of Japan were tested in an extensive world wide echo canceller field trial in 1974<sup>[23]</sup>. The portion of this trial involving two experimental echo cancellers used at the ends of international satellite links between the UK and the US are described here. Tests were performed simultaneously on satellite circuits equipped with the echo cancellers (designated by the nomenclature EC/S), satellite circuits equipped with the fully compliant CCITT G161 echo suppressors (ES/S), and submarine cable circuits equipped with the echo suppressors (ES/C). Data on customer opinion was obtained by calling back the destination

customer within one hour of call completion and asking him (or her) their opinion of the call in terms of the opinion scale Excellent (4), Good (3), Fair (2), and Poor (1), then inquiring if they had difficulty and, if the response was yes, what was the cause of the difficulty.

#### 1.8.1.2 Subscriber Opinion Results

The distributions of the responses are given in Figure 14. Part (A) gives the response distributions for US customers talking to UK customers in London, part (B) those for US customers talking to UK customers outside of London and (C) for UK customers talking to New York, US customers.

Analysis of these distributions shows that:

- 1) For US customers talking to UK customers in London, the echo canceller equipped satellite circuits performed significantly better than those equipped with echo suppressors and performed as well as the echo suppressor equipped cable circuits.

- 2) For US customers talking to UK customers outside of London, the echo canceller and echo suppressor equipped satellite circuits performed about the same and the echo suppressor equipped cable circuits performed better than either of the satellite circuits.

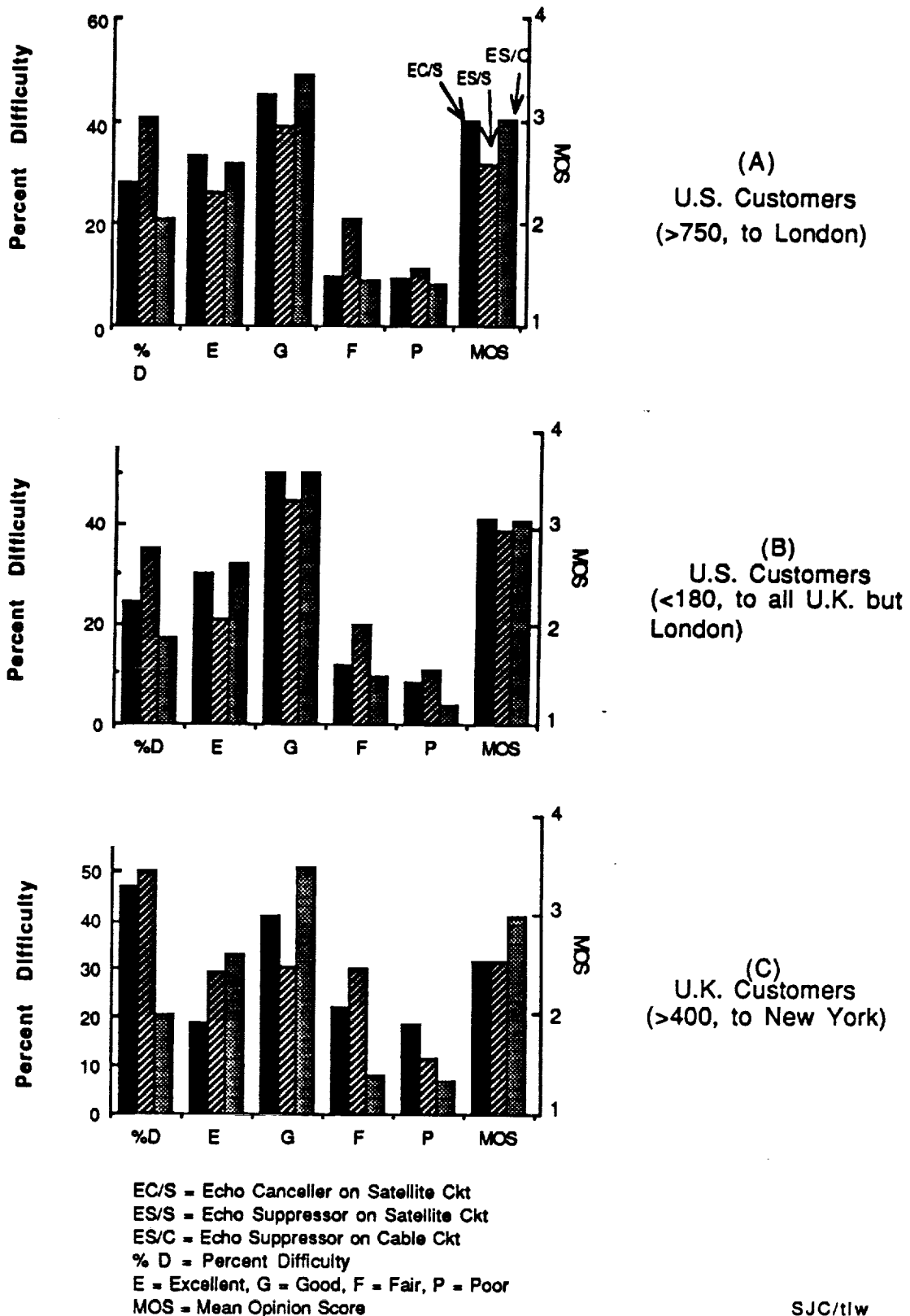
- 3) For UK customers talking to New York customers, the echo canceller equipped satellite circuits performed significantly better than the echo suppressor equipped satellite circuits and performed as well as the echo suppressor equipped cable circuits.

#### 1.8.1.3 Discussion of the Results

This first test of echo cancellers in the actual operating environment indicated that:

- 1) The echo cancellers performed well and delivered improved performance compared to echo suppressors when the terminating circuits have normal speech and noise levels. This is the condition that was encountered for the customers in London and New York.

Figure 14. Distribution of Customer Interview Responses for Six Populations



SJC/tlw

2) When the terminating circuits were abnormal (as was the case for circuits terminating to locations outside London over connections that were admitted to be lower in level and noisier than desired by the British Post Office) the performance advantage of the echo canceller was lost.

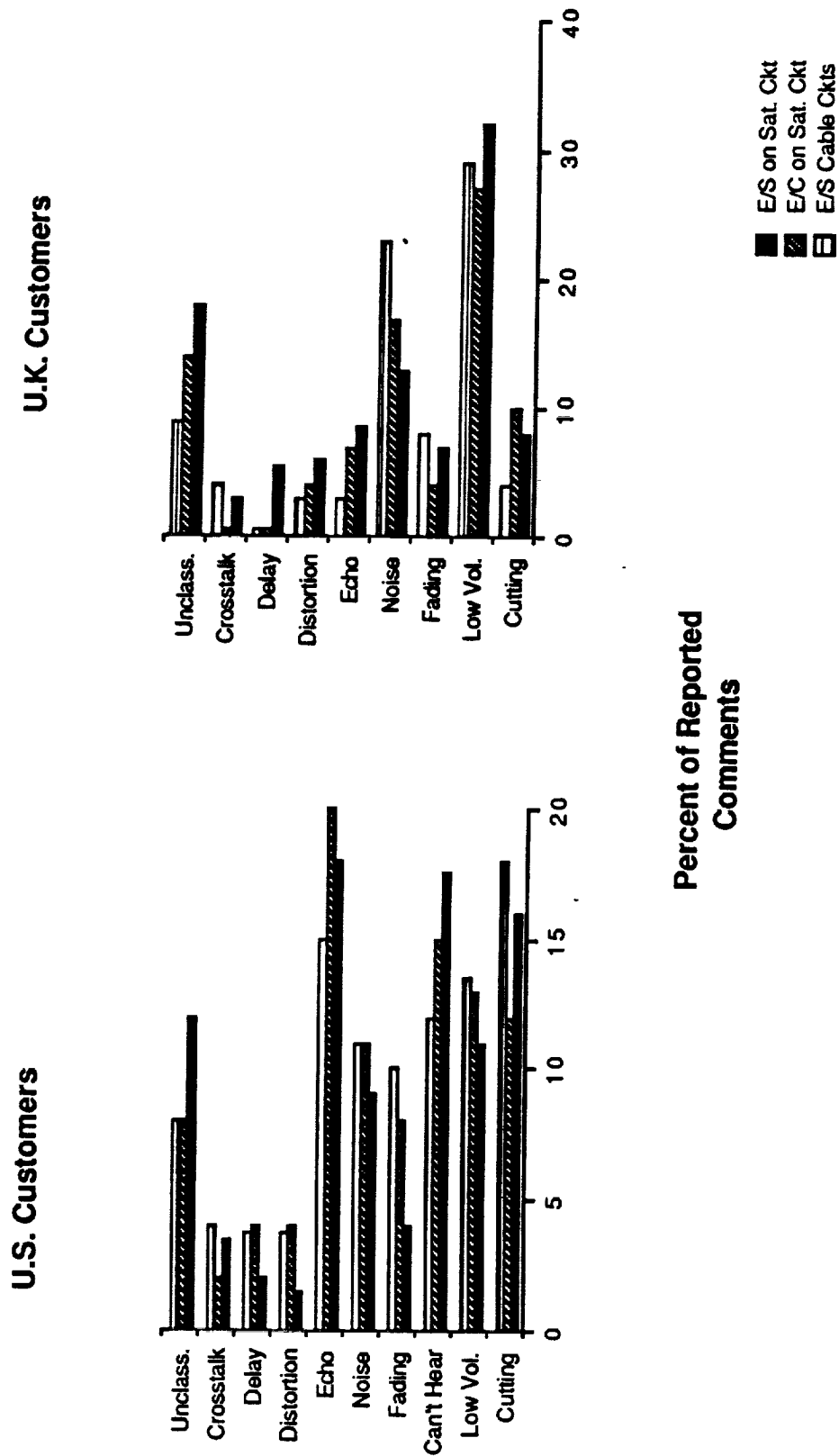
3) Satellite circuits proved to be less tolerant to the degradations caused by echo suppressor operating nuances and degraded performance of the terminations between the interface to the long-lines facilities and the customer location than did the cable circuits. This is attributed to the longer propagation delay of the satellite circuits.

The distributions of the causes of difficulty identified by the UK and US customers in the total samples collected for each of the three circuit conditions are shown in Figure 15. These distributions clearly point to cutting, low volume (including "can't hear") and echo as the principal causes of difficulty. Delay is infrequently identified as a cause. Also, the US customers identified echo much more frequently as a cause of difficulty than the UK customers for reasons that were never determined. This may have been due to unwanted coupling between the receive and transmit paths between the switching center in London where the cancellers were located and the interface to the satellite or submarine cable transmission facility.

#### 1.8.1.4 Conclusions

Echo cancellers improve the performance of long delay circuits when the causes of degradation are due to echo and the undesirable operating nuances of the echo suppressors, viz. echo spurts, passage of echo along with return side speech and speech chopping. Evidence of this is contained in data on the causes of difficulty. Delay is identified far less frequently as a cause of difficulty. When the degradations are due to low level and/or noise encountered on the terrestrial connections between the location of the echo control device and the location of the subscriber-- as was the case for the calls to subscribers outside of London--, the echo canceller performance improvement is lost. This was evidenced by the observation of little difference in subscriber opinion of the quality or indication of difficulty between echo suppressor and echo canceller equipped satellite circuits. Under the same circumstances,

**Figure 15. Typical Examples of Reported Difficulties**





the echo suppressor equipped cable circuit always out performed the satellite circuit. This indicates that the satellite circuit is less tolerant to the degradations. Conversely, the satellite circuit quickly responds to the improved performance provided by the echo cancellers and improved quality on the tail circuits connecting the customers.

## 1.8.2 Satellite and Terrestrial Circuits in U.S. Domestic Service.

### 1.8.2.1 Organization of The Tests

From July 1976 to February 1977 the Bell System performed call-back tests to customers of its US national network using satellite, terrestrial and composite (satellite one-way and terrestrial the other) circuits between Pittsburgh and Atlanta and Pittsburgh and San Francisco<sup>[24]</sup>. In the Pittsburgh-Atlanta tests, simple loss was used to control echo on the terrestrial circuits, 4A suppressors and Echo Suppressor Terminals on the composite and satellite circuits, and the echo canceller on satellite circuits. Because of the longer path, the 4A suppressor was used on terrestrial circuits between Pittsburgh and San Francisco, while the composite and satellite circuits were the same as those in the Pittsburgh-Atlanta tests.

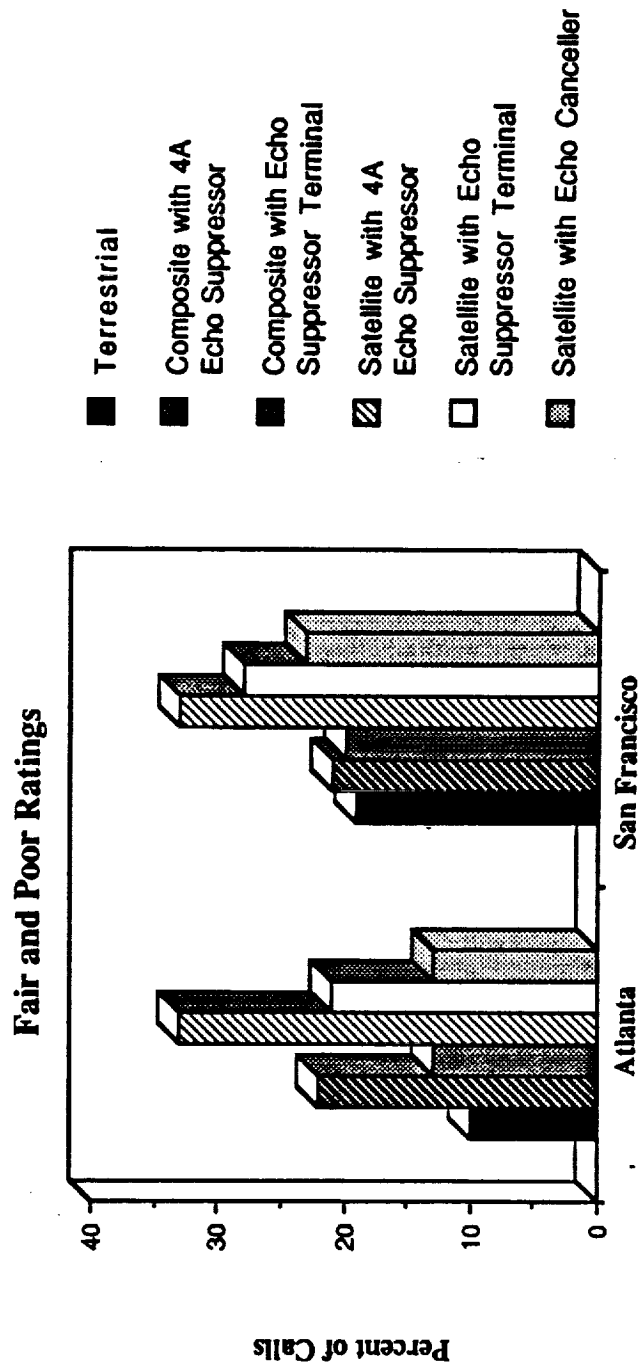
Telephone interviews with customers were the key part of the testing. Recipients of calls in Atlanta and San Francisco were interviewed about 15 minutes after hanging up, and the typical interview lasted three to four minutes. In the interview, customers were asked to rate the connection quality on the four point scale Excellent, Good, Fair, Poor and to identify a number of specified impairments they may have noticed.

### 1.8.2.2 Subscriber Opinion Results

The results in terms of the percentage of Fair plus Poor ratings are given for the various conditions in Figure 16. The summary of results are:

- 1) The terrestrial and echo canceller equipped satellite circuits were equivalent in performance and both achieved the lowest percentage of Fair plus Poor ratings.

**Figure 16. Interview Results from AT&T Domestic Circuits Tests**



- 2) Composite circuits with the digitally implemented Echo Suppressor Terminal also gave service equivalent to that of terrestrial circuits, primarily because the echo was reduced so effectively and the delay was half that on all-satellite circuits;
- 3) Satellite circuits with the 4A echo suppressor resulted in the worst performance.
- 4) The Echo Suppressor Terminal performed distinctly better than the 4A suppressor on satellite circuits. However, the service was not as good as that on terrestrial facilities;
- 5) On composite circuits, performance with the 4A suppressor was somewhat better than that over all-satellite circuits using the 4A suppressor.

#### 1.8.2.3 Conclusions

These results clearly demonstrated that echo-canceller-equipped satellite circuits operating in the AT&T US domestic network performed as well as terrestrial circuits. They also identified that the 4A echo suppressors, which conformed with the CCITT G 161 recommendation for long propagation delay circuits, produced impairments to speech transmission such as chopping and spurts of echo that degraded the performance of the circuits on which they were used. New digitally implemented echo suppressors which operated with shortened hangover times and improved logic for the control of echo suppression and break-in also improved the performance but not to the same extent as the echo cancellers. Tests were also performed on composite circuits in which satellite links are used in one direction and terrestrial links in the other. This significantly reduces the roundtrip propagation delay. The results for the composite circuits which were tested only with the echo suppressors were better than for the full satellite circuit with the same echo suppressors but not better than the echo canceller on the full satellite circuit.

During this test the terrestrial extension circuits were maintained according to the usual high standards of the AT&T system and were never a source of degradation. This situation favored the echo canceller since its capability to eliminate echo

without undesirable attendant operating nuances was not impaired by poor terrestrial extension quality.

### 1.8.3 Subjective Evaluation Of Echo Control Methods By AT&T

AT&T presented a survey of satellite user reaction to echo control methods in a contribution to the CCITT in June 1979 that summarized a number of tests involving analog and digital echo suppressors and echo cancellers in the US domestic settings[25]. Some of the results were derived from the same testing effort comparing echo suppressors and echo cancellers given in the previous section, but were significantly expanded for the CCITT contribution. The results of these tests concluded that:

- a) The problems experienced by telephone users are primarily due to echoes occurring in the presence of the long propagation delay inherent in geo-synchronous satellite systems.
- b) It is possible to reduce the impairment effects of delayed echoes to acceptable performance levels using Echo Cancellers or by engineering Half-Hop satellite circuits (one-way via satellite, one-way via terrestrial facilities), using Digital Echo Suppressors.
- c) Telephone users steadily increase their overt actions (Terminate Calls Early, Redial Calls or Redial Operators for Assistance) as they reduce their subjective opinion of the connection quality.

#### 1.8.3.1 Test Organization

A call-back telephone interview, conducted primarily with the called parties (a few were conducted with calling parties also), containing the following questions provided a basis for subjective transmission quality measures:

- a) Was the quality of the connection acceptable to you?

If yes, question (b) was asked.

If no, the interviewer skipped to question (c).

- b) Did you have any difficulty talking or hearing over that connection?
- c) Which of these four words comes closest to describing the quality of that connection: Excellent, Good, Fair or Poor?

If the respondent answered "No" to question (a) or "Yes" to question (b), the following questions were asked:

- d) Did this cause you or the other person to end your conversation:

If "Yes", question (e) was asked.

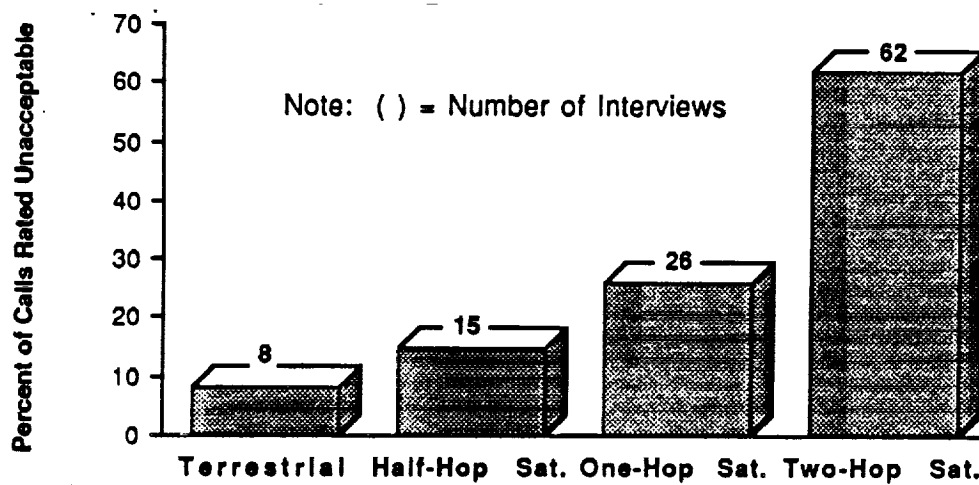
- e) Did you or the other person call back to complete your conversation?
- f) Did you or the other person contact the operator to inform her of the difficulty or to request assistance?

#### 1.8.3.2 Results For Old Echo Control Technology

The echo suppressor (old CCITT G.161 analog type) results obtained in the six domestic tests are combined to form a composite of user reaction as shown in Figure 17 for Terrestrial, Half-Hop, One-Hop and Two-Hop satellite configurations. The composite results are for circuit conditions using VNL design and conventional analog echo suppressors. Results are expressed in terms of the percent of connections which were rated Unacceptable (%U) by customers who were engaged in normal conversations on calls they received. Over 6400 customer interviews are included. Of 2414 interviews conducted for the Terrestrial test circuits, 8.3% of the connections are rated Unacceptable. Of 1255 interviews for Half-Hop circuits, 14.9% are rated Unacceptable. For 2005 interviews for One-Hop satellite circuits, 26.0% are rated Unacceptable and 62.0% or nearly two-thirds of the 753 interviews conducted for Two-Hop satellite circuits are rated Unacceptable. In general, customers rated the Half-Hop circuits Unacceptable twice as often compared and two-Hop connections nearly eight times more often.

**Figure 17. Domestic Satellite User Reaction Tests**  
**Composite Results**

(Using Conventional Echo Suppressors)



### 1.8.3.3 Results For New Echo Control Technology

During the Phase 1 COMSTAR tests, two new echo control devices were evaluated, the #4 ESS digital echo suppressor and experimental echo cancellers. Figure 18 presents the composite results for the test circuits equipped with the new echo control devices. Conventional echo suppressors, the #4 ESS digital echo suppressors and echo cancellers are designated by the abbreviations ES, DES and EC respectively. There are three important findings shown in Figure 18:

- a) The digital echo suppressor provides service on Half-Hop satellite circuits comparable to terrestrial service (8.7 vs. 8.3 %Unacceptable). The digital echo suppressor improves performance on One-Hop satellite circuits when compared with the conventional echo suppressor results (17.3 vs. 26.0 %Unacceptable).
- b) The echo cancellers provide service on One-Hop satellite circuits nearly equivalent to the terrestrial results (9.5 vs. 8.3 %Unacceptable).
- c) The echo cancellers provide marked improvement in the quality of Two-Hop satellite circuits (21.3 vs. 62.0 %Unacceptable).

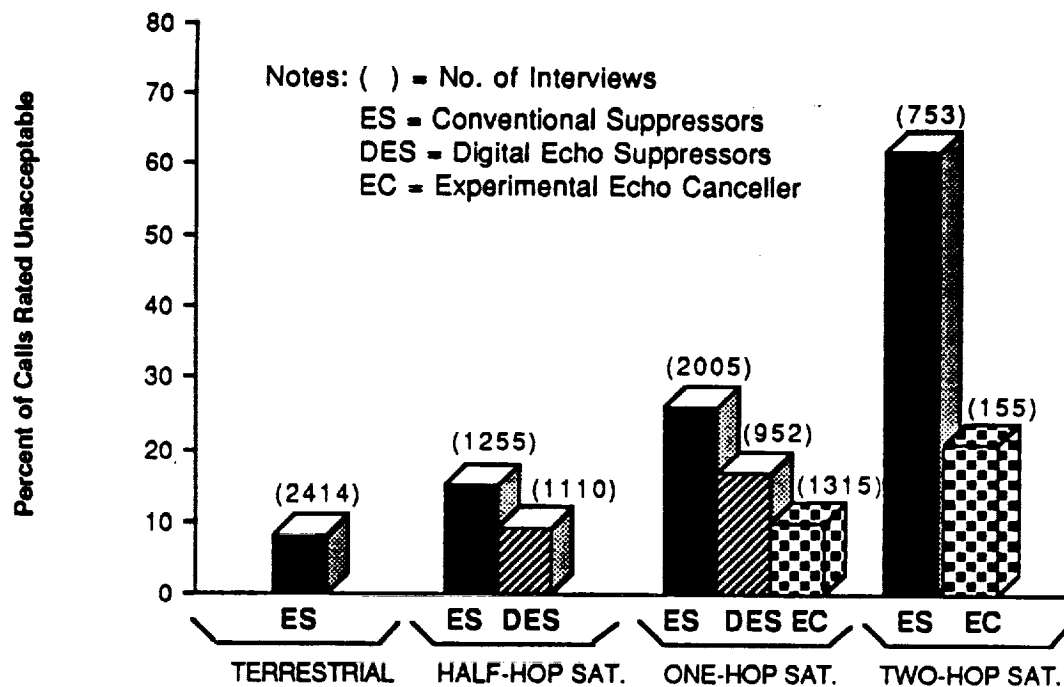
### 1.8.3.4 Calls Terminated Early

Composite results for the percent of calls which customers declared were terminated early for conventional echo suppressors are:

- 1.6 % for the Terrestrial benchmark,
- 3.1 % for the Half-Hop Satellite and
- 6.4% for One-Hop Satellite operation.

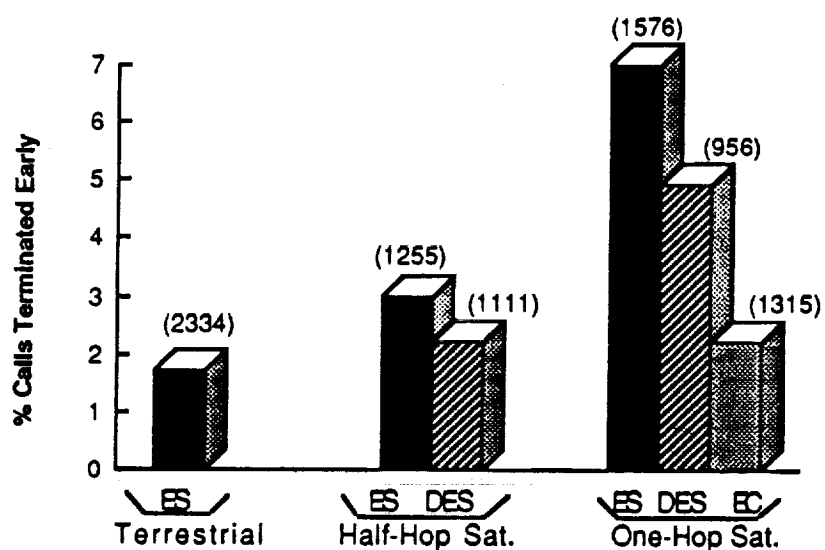
These results track with the 2:1 and 3:1 ratios of the Unacceptable ratings given in Figure 19. This is a more critical result which implies that customers take some action when they receive poorer quality transmission.

**Figure 18. Domestic Satellite User Reaction Test Results**  
(Using New Echo Control Methods)





**Figure 19. Domestic Satellite User Reaction Test Results  
Compares Echo Control Methods**



Notes: ( ) = Number of Interviews  
 ES = Conventional Suppressors  
 DES = Digital Echo Suppressor  
 EC = Experimental Echo Canceller

The digital echo suppressor improves performance to:  
2.1% for Half-Hop satellite operation and  
4.9% for One-Hop satellite operation.

The Echo Canceller, with 2.0% of the calls being terminated early, ranks superior to the conventional echo suppressor devices.

Due to the small number of occurrences for the terminated early category, the Digital Echo Suppressor on Half-Hop and the Echo Canceller on One-Hop satellite circuits are considered comparable to the Terrestrial performance, consistent with the results in Figure 18 for the Unacceptable ratings.

#### 1.8.3.5 Conclusion

The large data base of nearly 10,000 user interviews reported in this contribution demonstrate that:

- a) Telephone users experience Difficulty or Unacceptable service two to three times more often on satellite circuits equipped with analog echo suppressors than they do on conventional terrestrial circuits.
- b) The difficulties experienced by telephone users are primarily due to echoes occurring in the presence of the long propagation delay inherent in geo-synchronous satellite systems.
- c) It is possible to reduce the impairment effects of delayed echoes to near-terrestrial performance levels using Echo Cancellers on One-Hop satellite circuits. Similar findings have been substantiated in previous contributions to CCITT[17].

#### 1.8.4 Compatibility of Echo Suppressors with Echo Cancellers on Satellite Circuits

During April-August 1978 the TransCanada Telephone System (TCTS), a member of the Canadian Telecommunications Carriers Association, carried out an extensive experiment on the use

of echo suppressors and echo cancellers on terrestrial and ANIK 'A' domestic satellite circuits in the Canadian telephone network. Bell-Northern Research (BNR) designed the experiment and analyzed the test data. A report on the results was presented by Canada to CCITT Study Groups XII, XV, and XVI in April 1979[26].

The results of subjective tests for satellite circuits equipped exclusively with half-echo suppressors or echo cancellers are presented. Also the results for a particular circuit configuration of the experiment, termed the "satellite combination circuit" which comprised a satellite circuit equipped at one end with an echo suppressor and at the other end with an echo canceller are presented. Such a circuit could form part of an international connection where one administration uses an echo suppressor and the other administration uses an echo canceller.

#### 1.8.4.1 Organization Of Tests

The tests were conducted using two satellite circuits set up between Toronto, Ontario and Vancouver, British Columbia equipped for the configurations identified above. The airline distance and terrestrial routing distance between Toronto and Vancouver is 3700 km and approximately 4800 km respectively and terrestrial circuits on this route are usually equipped with echo suppressors.

Call back interviews based on standard procedures documented in CCITT Recommendation P.77 and E.425 were conducted with the calling (Toronto) and called (British Columbia) customers.

To assess the transmission quality of the connection a trained interviewer asked each customer, who finished a call over the circuit under test, two basic questions for analysis.

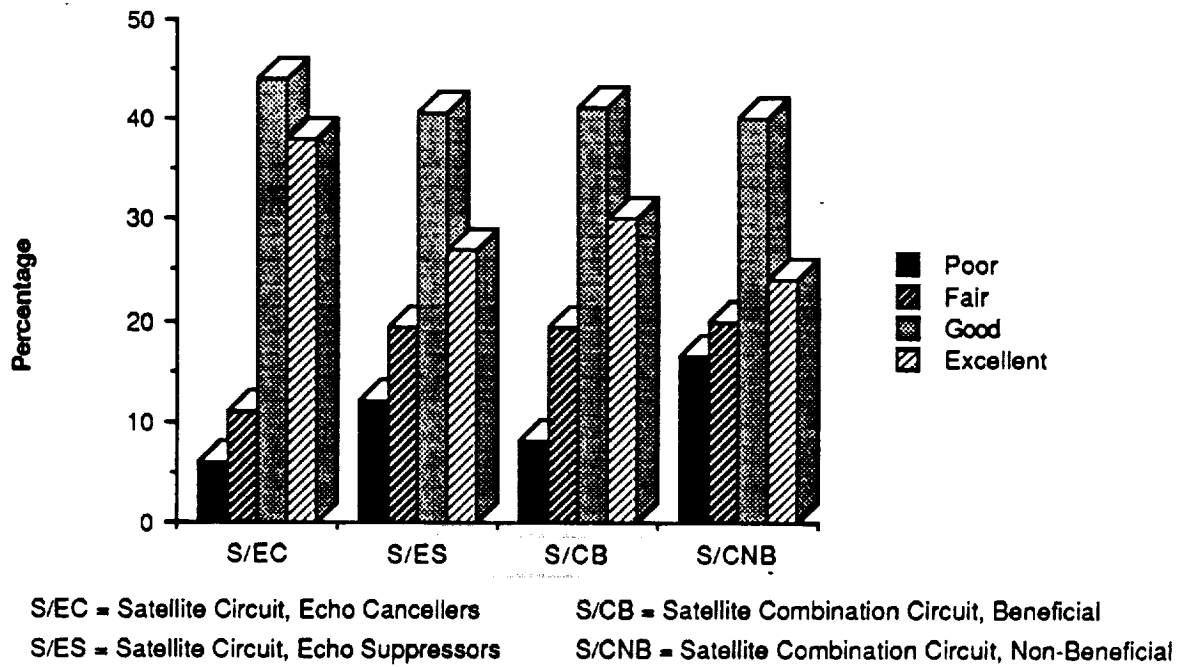
- (i) Which of these four words comes closest to describing the quality of the connection during the conversation? Was the connection: Excellent, Good, Fair, or Poor?
- (ii) Did you or the person you were talking to have any difficulty in talking or hearing over the connection?

#### 1.8.4.2 Results of Subjective Tests

The test results for satellite circuits equipped exclusively with either half-echo suppressors or echo cancellers are based on over 300 interviews for each condition, whereas for the satellite combination circuits more than 100 interviews were conducted for each circuit end, the beneficial (CB) ends equipped with half-echo suppressors and the non-beneficial (CNB) ends equipped with echo cancellers. Recall that an echo control device located at one end of a circuit benefits the subscriber at the opposite end.

For each test a computation was made of the percentages of customers responding "excellent", "good", "fair" or "poor". These results are shown in Figure 20. Computation results of the percentage difficulty and the "Mean Opinion Score" (MOS) for each test condition are presented in Table 6. Also indicated in Table 6 is the 95% confidence interval for the MOS. Discussion of Test Results.

**Figure 20. Distribution of Responses for the Canadian Echo Control Tests**



The test results show that circuits equipped at both ends with echo cancellers achieved the best ratings and those with the echo suppressors at each end the poorest. Regarding satellite combination circuits, a significant difference in performance between the beneficial and the non-beneficial end of connections was observed.

TABLE 6

Quality Evaluation of Satellite Circuits Equipped with  
Echo Cancellers, Half-Echo Suppressor, a Combination of Both

Condition	S/EC	S/ES	S/CB	S/CNB
No. of Interviews	315	329	123	109
% Poor	6	13	8	17
% Fair	12	19	20	20
% Good	44	41	41	39
% Excellent	38	27	31	24
% Difficulty	15	31	23	33
Mean	3.15	2.82	2.95	2.71
95% Confidence Interval	3.24-3.06	2.91-2.73	3.04-2.86	2.80-2.62

S/EC = Satellite circuit, Half-Echo Cancellers both ends

S/ES = Satellite circuit, Half-Echo Suppressors both ends

S/CB = Satellite circuit, Echo Canceller one end, Half-Echo Suppressor other end, Combination Beneficial (opinion of the customer at the suppressor end)

S/CNB = Satellite circuit, Echo Canceller one end, Half-Echo Suppressor other end, Combination Non-Beneficial (opinion of the customer at the canceller end).

The performance differences can be explained by the operating characteristics of echo suppressors and echo cancellers. During double talk the use of half-echo suppressors results in echo bursts and speech mutilation (e.g. chopping). The use of echo cancellers, however, results in echo removal without speech mutilation.

In general, the near-end echo control device is working for the benefit of the far-end customer. This means that on a combination circuit the customer at the half-echo suppressor end benefits from the echo canceller at the other end, while the customer at the echo canceller end experiences echo burst and speech mutilation due to the half-echo suppressor.

In the test, customers using the circuit equipped exclusively with echo cancellers achieved a mean opinion score (MOS) of 3.15 compared to 2.82 for those using the circuit equipped exclusively with echo suppressors. For the customers using the combination circuit, at the beneficial end rated the performance marginally better (MOS = 2.95) than that of exclusively half-echo suppressor equipped circuits (MOS = 2.82), but inferior to the performance on circuits equipped exclusively with echo cancellers (MOS = 3.15). The inferior performance rating relative to exclusively echo canceller equipped circuits can be explained by the reduction in speech volume during double talk due to the introduction of receive loss in the half-echo suppressor. Moreover it is possible that the performance rating at the beneficial end was indirectly influenced by difficulties experienced by the customer at the non-beneficial end.

Customers at the non-beneficial end of the combination circuit rated the performance marginally worse (MOS = 2.71) than that of exclusively half-echo suppressor equipped circuits (MOS = 2.82). These were the customers equipped with echo cancellers at their end of the circuit and echo suppressors at the far end. This can be attributed to inadequate attenuation in the echo path during double talk (receive loss of only one half-echo suppressor).

#### 1.8.4.3 Conclusions

Significant difference in performance exists between the two ends of satellite combination circuits. However, beneficial and non-beneficial performance ratings of satellite combination circuits are not significantly different compared to the performance rating of satellite circuits equipped at both ends with half-echo suppressors. Satellite circuits equipped exclusively with echo cancellers provide for a performance significantly better than satellite combination circuits (beneficial and non-beneficial) as well as satellite circuits equipped exclusively with half-echo suppressors.

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### 1.8.5 Subjective Performance Of A Private Telephone Network In the U.S.

COMSAT, with the cooperation of a US private telephone network operator performed subjective tests on customers using echo canceller equipped circuits with one-way propagation delays ranging from 45 ms to 500 ms. Tests were performed on satellite circuits and on terrestrial circuits<sup>[27]</sup>. Both arrangements were equipped for delay augmentation by artificial means. Subjective results were obtained by means of customer interviews conducted after call completion using the mean opinion score method based on responses to the question "How would you rate the quality of the service, Excellent, Good, Fair, or Poor?" and the response to the question "Did you have difficulty?"

The mean opinion scores obtained by the subjects on all delay conditions differed by only small amounts, ranging from 3.28 for 45 ms terrestrial circuits to 3.21 for 500 ms delay circuits. However, the reported percent difficulties increased from 6.9% for 45 ms, to 7.6% for circuits with 300 ms delay, and 15.8% for circuits with 500 ms delay, indicating increased difficulty with increased delay.

#### 1.8.5.1 Organization Of Tests

Two satellite circuits between Somerset, New Jersey and at Memphis, Tennessee were used. The test subjects were located at both ends of the circuit, but only the Memphis participants were interviewed for their comments and assessments. They were not aware of the test conditions and did not know each other. The satellite one-way delay was augmented artificially to yield one-way delays of 300 ms or 500 ms. Transmission incorporated a 32-kbit/s Nearly Instantaneous Companding (NIC) coding technique. Both ends of the circuit were equipped with echo cancellers conforming to Rec. G. 165. The distance from the switch to the telephone handsets varied between a few hundred feet to less than 2,000 feet. The echo return loss (without the cancellers) was about 18 dB. The transmit and receive transmission levels of the 4-wire circuits were at -16 dBr and +7 dBr and for convenience, the total additional round trip propagation delay was lumped in one direction.



The terrestrial test circuits were connected within the Memphis area. One way delays of 45, 300 and 500 ms were introduced by artificial means. The connections to the telephones were otherwise the same as for the satellite connections.

#### 1.8.5.2 Summary of Test Conditions

A total of five test conditions were used. Two of the conditions included a satellite link and the only variable was the propagation delay. The first condition  $S_1$ , incorporated a total one-way delay of 300 ms while the second condition  $S_2$  incorporated similarly a total MOPT of 500 ms.

The remaining three test conditions used the terrestrial connection, augmented by delay as required. The first terrestrial condition  $T_0$  included a one-way propagation time of 45 ms. This was selected to establish a reference. The second and third terrestrial conditions  $T_1$  and  $T_2$  included one-way delays augmented to 300 ms and 500 ms, respectively. These two conditions were used to provide a check on the test results obtained on conditions  $S_1$  and  $S_2$  (the latter included 32 kbit/s NIC coding in the transmission paths).

#### 1.8.5.3 The Subjective Tests

Conversational subjective tests were conducted on the five test conditions described above. The test procedure was as follows. Trained callers contacted subjects (company employees) and conducted conversations by offering subjects a list of topics of current national interest from which to choose. Conversations lasted an average of about 4.5 minutes. Immediately following the conversation, an interviewer made a callback interview as prescribed in CCITT Rec. P.77, Annex A to obtain the rating of the quality of the connection (excellent, good, fair, poor and bad) and inquiring about difficulty and its causes.

For each of the test conditions, more than one hundred completed interviews were obtained. The results were then used in the computation of mean opinion scores (MOS) and percent difficulty for each of the test conditions.

#### 1.8.5.4 Subjective Test Results

The terrestrial circuit with 45 ms one-way delay achieved an MOS of 3.28 and a percent difficulty of 6.9% which were the best scores obtained in the test. The test data S<sub>1</sub>, T<sub>1</sub> for 300 ms one-way delay and S<sub>2</sub>, T<sub>2</sub> for 500 ms one-way delay are given in Table 7. The MOPT results obtained for satellite and terrestrial circuits with augmented delay conditions are all in a narrow range about 3.22 and are not statistically significantly different. Percent Difficulties are all low, ranging from 5% and 10% for the 300 ms conditions to 15.6% and 15.9%. These differences are not statistically significant but do indicate a low overall occurrence of difficulty for the universal test results.

TABLE 7  
TEST DATA FOR CIRCUIT CONDITIONS

S <sub>1</sub> Satellite with 300 ms delay											
T <sub>1</sub> Terrestrial with 300 ms delay											
S <sub>2</sub> Satellite with 500 ms delay											
T <sub>2</sub> Terrestrial with 500 ms delay											
Type of Circuit	MOPT, ms	No of calls	Ratings						MOS	Percentage Difficulty	
			E	G	F	P	B				
S <sub>1</sub>	300	117	4	1	6	4	9	3	0	3.22±0.13	5.1
T <sub>1</sub>	300	108	3	8	6	2	8	0	0	3.27±0.12	10.2
S <sub>2</sub>	500	113	3	7	6	6	8	2	0	3.22±0.12	15.9
T <sub>2</sub>	500	109	3	6	6	3	7	2	1	3.20±0.14	15.6

#### 1.8.5.5 Conclusions

The circuits used in these tests were of very high quality with terminations exhibiting an inherently high echo return loss (18 dB) operating into echo cancellers that totally eliminated echo. The signal levels were all well within tolerance and the noise introduced on the facilities was very low. Therefore, it is not surprising that the users gave excellent ratings to the service they experienced as evidenced by the above data on circuits with one-way delays of 300 and 500 ms. This further supports a conclusion that delay by itself is

not a principal cause of dissatisfaction or difficulty to users of long propagation delay circuits.

## 1.9 SUMMARY AND CONCLUSIONS

Results of human factors and subjective reaction studies in the laboratory and in field tests using operational facilities described in the foregoing report indicate that echo by far is the chief cause of difficulty in long propagation delay telephony. Switching nuances attending echo elimination by echo suppressors frequently leave the speech signal mutilated and are a predominate cause of subscriber dissatisfaction. Either of these echo related impairments are exacerbated by long propagation delay. However, when echo is eliminated and propagation delay is the only remaining factor, the difference in the subjective opinion of the performance of long and short propagation delay circuits is virtually insignificant.

Human factors studies indicate that propagation delay taken in isolation will begin to influence conversational speech flow patterns for delay times in excess of a few hundred ms. However, in laboratory tests, the subjects rarely become aware of propagation delay even for delays in excess of those of double hop satellite circuits (1200 ms round trip delay). Field tests conducted on operational circuits, where the subjects are paying subscribers, exhibit no difference in quality assessments and indication of difficulty between single hop satellite and terrestrial circuits in both domestic and international operation when echo is eliminated by echo cancellers. However, if echo exists or echo control means are used that occasionally admit echo or mutilate the speech (chopping and clipping) the circuits exhibit decreasing quality assessment scores and increasing difficulty or unacceptability with increasing propagation delay.

The results of the field tests obtained from subscribers using operational links, support the conclusions that echo, mutilation of the speech signal, echo under speech and echo spurts due to the properties of echo suppressor operation are the major causes of unacceptability and difficulty to subscribers using long propagation delay circuits. There is also strong evidence that excessive losses and noise on circuit terminations also contribute to customer dissatisfaction. When echo suppressor and terrestrial faults do occur, both short delay terrestrial circuits and long delay satellite circuits suffer, but satellite circuits are more adversely affected. However,

when echo is eliminated by use of echo cancellers and the quality of the terminations is within nominal limits expected of professional telecommunications plant acceptance and maintenance testing, the subscriber's opinion of satellite circuits differs little from that for short propagation circuits.

Acceptable use of satellite circuits for voice telephony requires elimination of echo without side effects and terrestrial terminations operating with nominal loss and noise level.

The dissatisfaction expressed in the early 1980s by users of satellite circuits provided by US independent carriers occurred at a time when the telephone companies were not required to provide equal access. The cause of the dissatisfaction may well have been partly due to poorly maintained terrestrial connections to the subscribers. With today's equal access requirement, satellite circuits used by private companies and independent carriers, equipped with echo cancellers, should perform far better.

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# Addendum 1

## Impact of Propagation Delay on Data Transmission

S. J. Campanella and D. M. Chitre

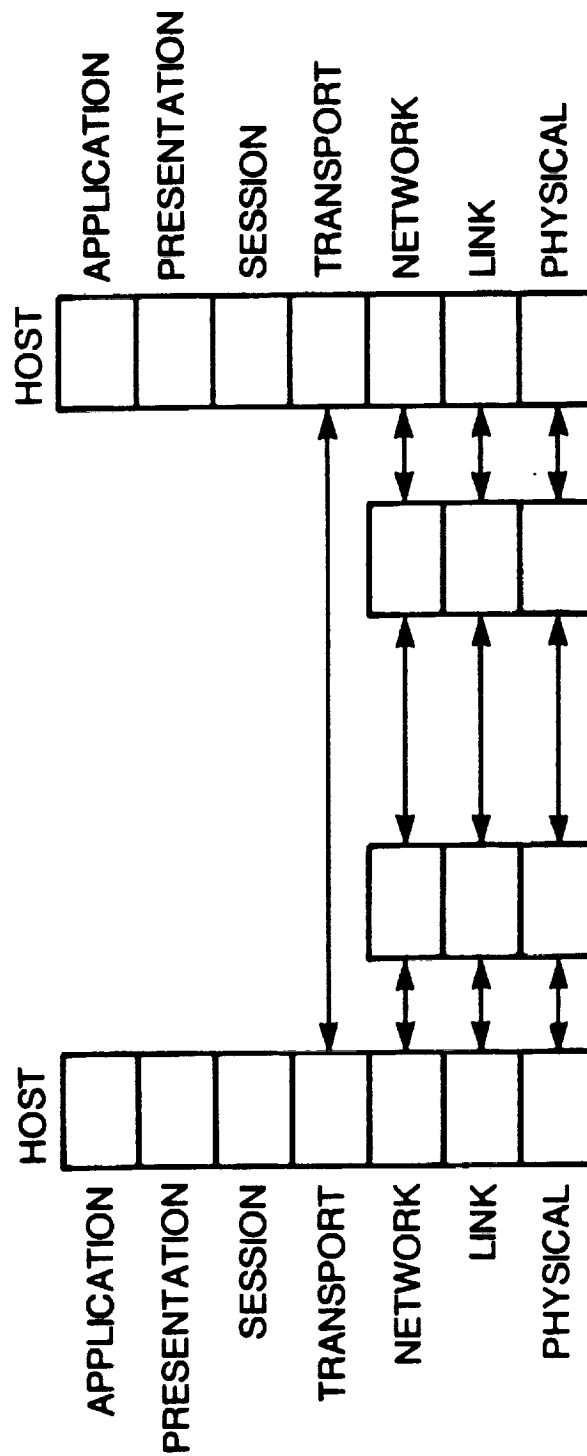
### A1.0 INTRODUCTION

Many applications of data communications between computing devices or terminals require a very high degree of data integrity. This requirement has resulted in various specific procedures in the communication protocols for error control. The International Standards organization (ISO) has developed a seven-layer reference model for computer communication protocols shown in Figure A1. The major error detection and recovery procedures are specified in layer 2 and layer 4, called link and transport layers, respectively. In the following, the impact of propagation delay on computer communications is first discussed from a general perspective. This is followed by a discussion of the specific operating aspects of current protocols used at the layer 2 and layer 4 levels. Finally, a discussion of possible improved protocols is presented.

### A1.1 PROPAGATION DELAY IMPACT

What is the impact of propagation delay on data transmission? It depends on a number of parameters of the transmission link which are listed as follows in the order of importance: 1) the protocol procedure and its parameters (modulus size, number of packets outstanding), 2) the method of error protection used (such as Go-Back-N, selective repeat or none at all), 3) the bit rate and error rate on the transmission link and 4) the magnitude propagation delay over the link. Consider first the impact of propagation delay. One of the most important applications of data communications is encountered when a computer terminal exchanges requests and responses with a remote host computer. In this very popular application the question arises, will the response time over a single hop satellite link aggravate the user compared to the response time with no delay? Users of computer terminals will almost

Figure A1. ISO Reference Model



universally agree that adding a half-second (the time it takes to say "one-oh-one") to the response time of a typical request-and-response exchange is of trivial significance. Indeed, it is not the augmentation of the transaction time that is of significance. Rather, it is the difficulty caused by the combination of propagation delay and the protocols used.

For certain data transmission requirements, such as for information from deep space vehicles, absolute error free protection is not required and it suffices to achieve a certain level of bit error rate for some stated fraction of time. An example is maintaining an error rate of 1 in  $10^7$  for 99.9% of the time. In such cases, forward error correction methods are sufficient for accomplishing the needed level of error protection and these are insensitive to propagation delay.

However, the largest fraction of data transactions used in what is popularly called the "computer communications market place" are expected to be absolutely error free even when transmitted over a link that may have a bit error rate as poor as 1 in  $10^4$ . Accomplishing this requires use of error detection coding of data blocks using procedures that will discover any combination of error bits in the coded message. If no errors are discovered then the message is accepted and acknowledged (called an ACK). If one or more errors are discovered the message is not acknowledged. Implementation of this acknowledgement procedure in conjunction with the Go-back-N protocol constitutes the method used in the X.25 protocol procedure and as explained below is highly sensitive to propagation delay and error rate. An alternate method called selective-repeat uses messages that identify specific packets not received and retransmits only these. This significantly reduces the sensitivity to error and propagation delay.

The salient link and transport layer protocols are described next and then analyzed from the point of view of the impact of satellite link propagation delay.

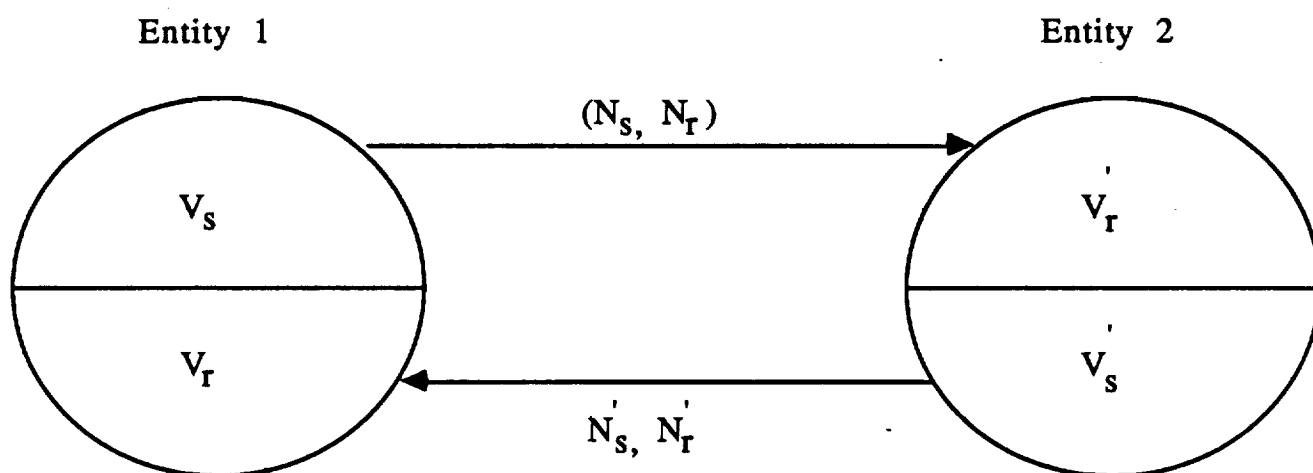
## A1.2 LINK AND TRANSPORT PROTOCOLS

### A1.2.1 High-level Data Link Control (HDLC) Protocol

The link layer protocol specified by the ISO is called HDLC [1]. The error recovery procedure in HDLC for a point-to-point link follows. Transmitted information data blocks, called I-frames, are numbered in sequence. I-frames are transmitted and received by entities in the network. Each entity maintains a "send state variable" ( $V_s$ ), which is the sequence number of the next I-frame to be transmitted to the next entity and the "receive state variable" ( $V_r$ ), which is the sequence number of the next I-frame expected to be received from the next entity. All I-frames contain the "send sequence number" ( $N_s$ ), identifying the frame being transmitted and the "receive sequence number" ( $N_r$ ) of the next expected I-frame to be received. The sequence number,  $N_r$ , indicates the acknowledgement of all I-frames with lower sequence numbers. The command and supervisory frames (called S-frames) also contain the receive sequence number. The situation between two entities is shown in Figure A2. Unprimed variables refer to entity 1 and primed to entity 2. Errors or data losses are detected at the receiving entity by comparing the  $N_s$  of the received I-frame with its local  $V_r$ . A value of  $N_s$  greater than  $V_r$ , indicates the loss of frame(s) and the received frame is ignored and  $V_r$  remains unchanged. If  $N_s$  and  $V_r$  match, the received frame is accepted and  $V_r$  is updated. The lost frames are recovered by issuing a "reject" (REJ) response with  $N_r = V_r$ , indicating the need to retransmit I-frame with sequence number  $N_s = N_r$  and all subsequent numbered I-frames. This is known as the "go-back-N" procedure, where N denotes the number of frames which are retransmitted after receiving a "reject" message.



Figure A2. HDLC ISO OSI LEVEL 2 DATA LINK PROTOCOL



The Go-back-N protocol procedure is implemented using a memory at the transmitter that holds up to N packets worth of data. N must be large enough to account for the number of packets that can occur during the round trip propagation delay of the transmission path.

The CCITT X.25 link access protocol procedure incorporates the ISO High-level Data Link Control (HDLC) procedure, which is a Go-back-N procedure to control packet transmission between a Data Transmission Equipment (DTE) and a Data Circuit-Termination Equipment (DCE). The value of N depends on propagation delay, packet size and transmission rate. Transmission of data packets of 1 Kbyte nominal size over channels of 64 Kbit/s rate with one-way propagation delays of up to 150 ms requires a value of  $N=5$  to accommodate packets stored in the path. Actually, the normal X.25 link access protocol provides for up to  $N=8$  packets outstanding which is suitable for terrestrial links. For long propagation satellite delays, the value of  $N \leq 8$  is too little to accommodate the one-way delay which can be up to 600 ms for double hop links. For this reason, the upper value of N has been increased to  $\leq 128$  for the extended X.25 link access protocol.

The extended X.25 provision permits the Go-back-N protocol procedure to operate over satellite links but it doesn't overcome a severe throughput penalty that attends Go-back-N operation over links with errors especially for large values of N. To see this, simply recall that the Go-back-N protocol procedure repeats the last N packets every time an error hits a packet. During the interval needed for this repeat, transmission of new packets ceases and average throughput is accordingly decreased. Obviously, as the value of N is increased, throughput decreases proportionately. Thus, the increase of N to  $\leq 128$  needed for long propagation delay satellite circuits is quite detrimental. This will be illustrated later.

A method known as selective repeat, in which only the packet suffering the error needs to be repeated, is a far better

solution for use over long propagation delay satellite circuits. This will also be discussed further in the following. Unfortunately, neither the ISO or the CCITT have elected to use the selective repeat method at the link access level. However, it is used at the transport level.

#### A1.2.2 Class 4 Transport Protocol

The ISO specified Class 4 Transport Protocol [2] incorporates the following selective repeat procedure for error recovery. Transmitted information data blocks called transport protocol data units (DT TPDU) are sequentially numbered. The transmitting transport entity sets a timer after delivering each TPDU to the lower layer for transmission. This timer, called the retransmission timer, determines when that TPDU will be retransmitted. It can be set appropriately to accommodate various propagation delays. The receiving transport entity sends acknowledgement messages (called AK TPDU) with the sequence number in each AK TPDU confirming the reception of all data DT TPDUs with lower sequence numbers. Notice that the receiving transport entity can store the out of sequence of DT TPDUs which have been received correctly. When the timer for a DT TPDU expires without an AK TPDU, it is selectively retransmitted. However, when there is a gap in the sequence number of received DT TPDUs, the DT TPDUs with sequence numbers beyond the gap cannot be acknowledged.

#### A1.3 PROTOCOL PERFORMANCE OVER SATELLITE TRANSMISSION PATHS

##### A1.3.1 Protocol Inefficiencies

The performance of each of the above protocols depends upon the channel capacity, bit error rate and the specific procedure of implementing the protocol. The inefficiency of the HDLC protocol for high bit rate and bit error rate over long delay links is caused by

the rejection of possible error-free frames and their retransmission following an erroneous frame. In the class 4 transport protocol (TP-4), unnecessary retransmissions occur after the expiration of retransmit timer for out of sequence TPDUs beyond the gap which cannot be acknowledged.

#### A1.3.2 Improving Performance

For improved satellite link performance over a wider range of bit rate and bit error rate, certain enhancements to the HDLC protocol are necessary. A protocol modified for satellite links, could store out of sequence data blocks in the receiver buffer and the sender could retransmit unacknowledged data blocks selectively[3]. The selective retransmission can be achieved by different procedures based on the characteristics of the underlying network. When the transmitter and receiver are connected by a direct link (no delay), a data block within a gap of received data blocks can be assumed to be lost (or damaged) and an explicit non-acknowledgement for that data block can be sent to the sender for its retransmission. However, when the transmitter and receiver are separated by intervening network(s) or routing nodes which introduce delay, the gap in the sequence numbers does not necessarily imply the loss of that data block. As this case is more likely to occur for an end-to-end communication protocol like transport protocol, two different methods are proposed for selective transmission. One method consists of modifying the acknowledgement procedure for selective acknowledgement of correctly received out of sequence data blocks[4]. The second method follows the procedures of the class 4 transport protocol with the following modified implementation of the retransmission timers. Whenever the timer for a data block with a specific sequence number expires, that data block is retransmitted and the timers for all the subsequently numbered data blocks are increased by the retransmission timer value.

The above implementation of the class 4 transport protocol or the modifications to the HDLC and class 4 transport

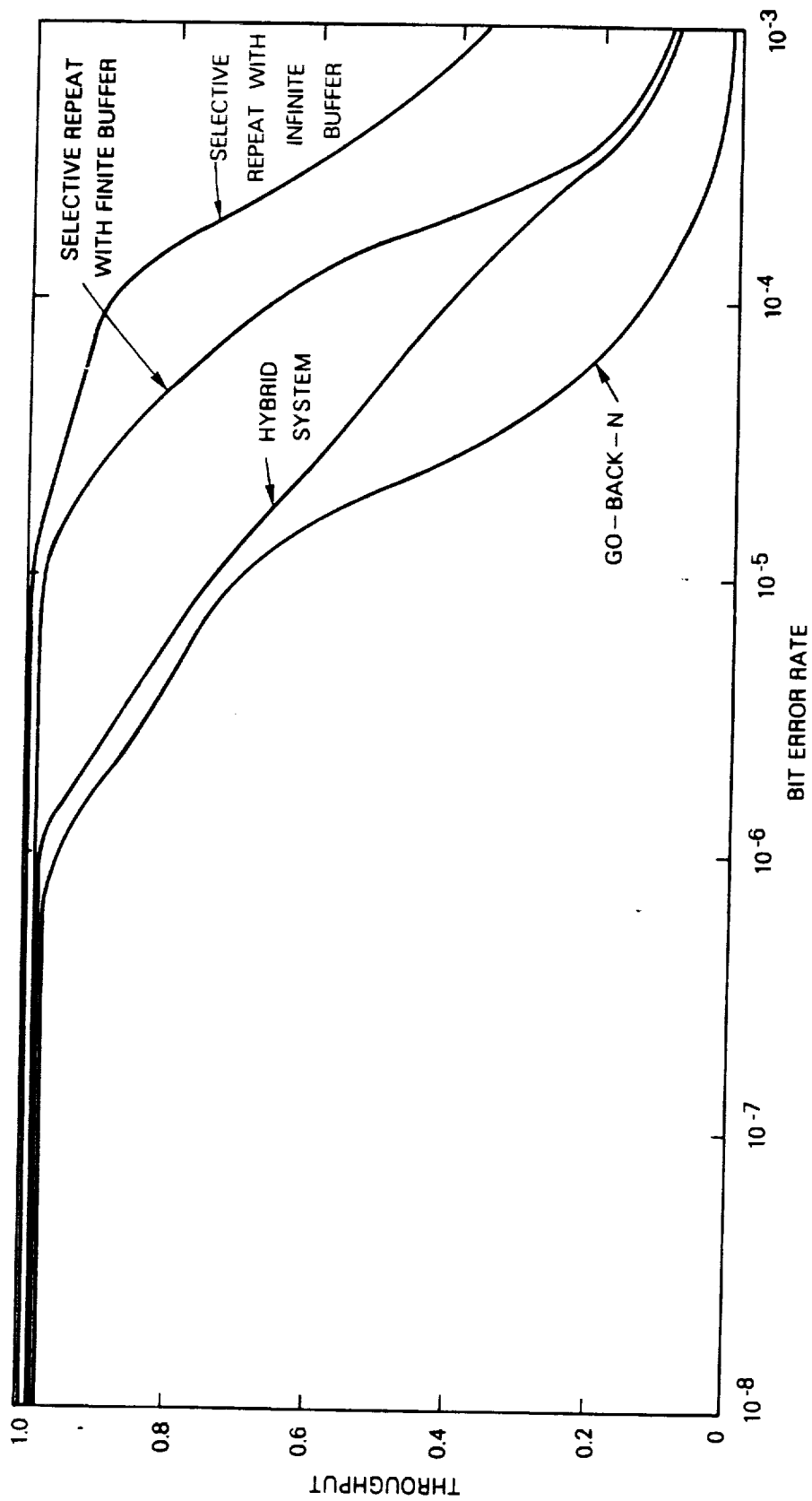
protocol reduce the unnecessary retransmissions of data blocks at the expense of storing out of sequence data blocks at the receiver. The impact of a finite memory buffer at the receiver on the performance of these protocols has been mathematically modeled and analyzed.

#### A1.3.3 Analysis of Improved Link Layer Protocols

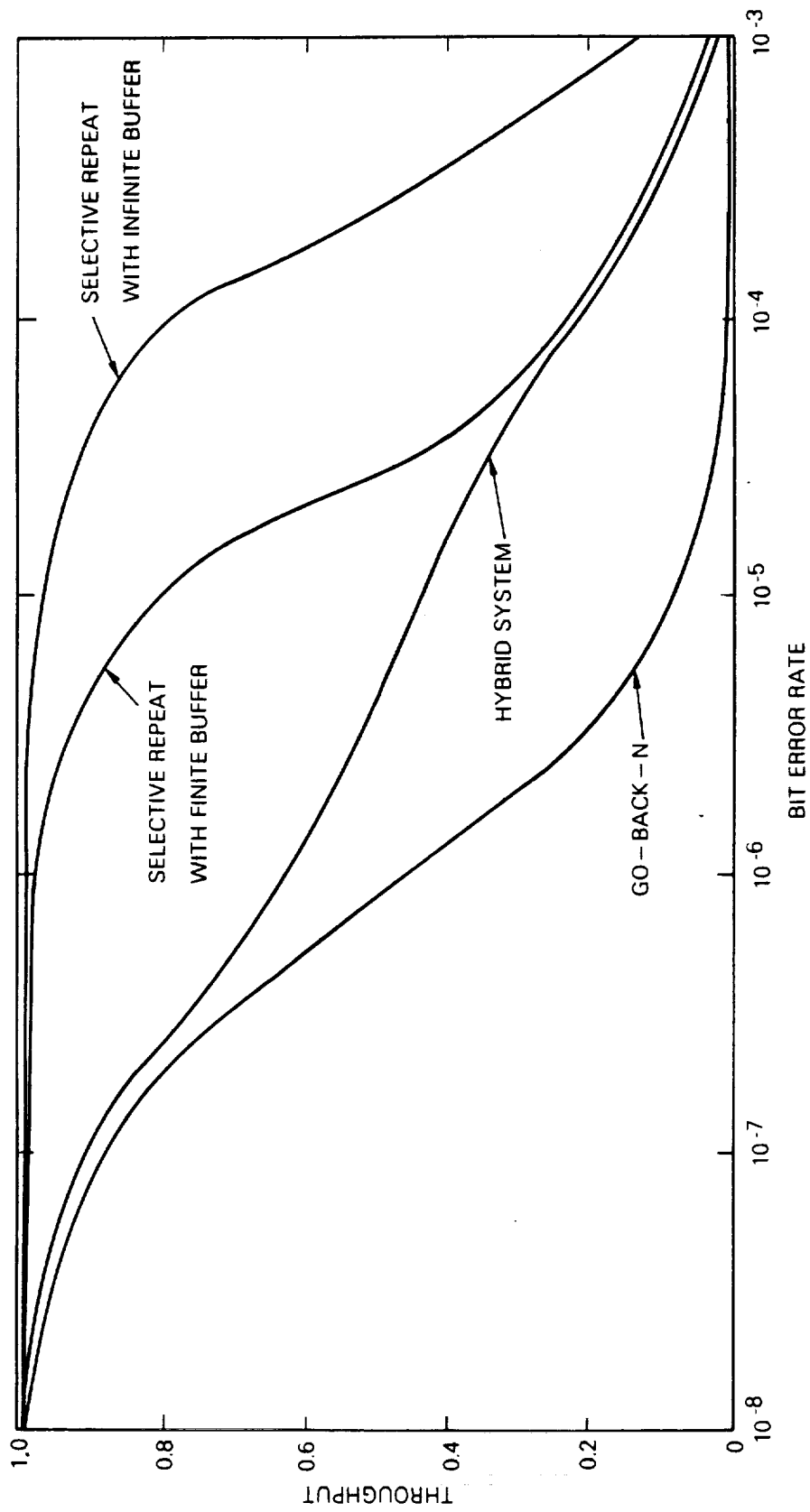
An analysis of four link layer protocol procedures over links with single hop delay has been performed. These included: (1) Go-back-N, (2) Selective Repeat with Finite Buffer, (3) Selective Repeat with Infinite Buffer and (4) a Hybrid combining Go-back-N and Selective Repeat. Figure A3 (#4 CTR) shows throughput efficiency for 1-Kbit block size over a 64 Kbit/s capacity channel, Figure A4 (#8 CTR) the ARQ delay for the conditions of Figure A3, Figure A5 (#7 CTR) the throughput efficiency with 2 Kbit block size and 1.544 Mbit/s channel capacity and Figure A6 (#11 CTR) the ARQ delay for the conditions of Figure A5. These curves illustrate the superiority of the selective repeat protocol procedures compared to the go-back-N method. ISO/OSI has yet to adopt the selective repeat methods at the link level.

#### A1.3.4 Analysis of Improved Transport Layer Protocols

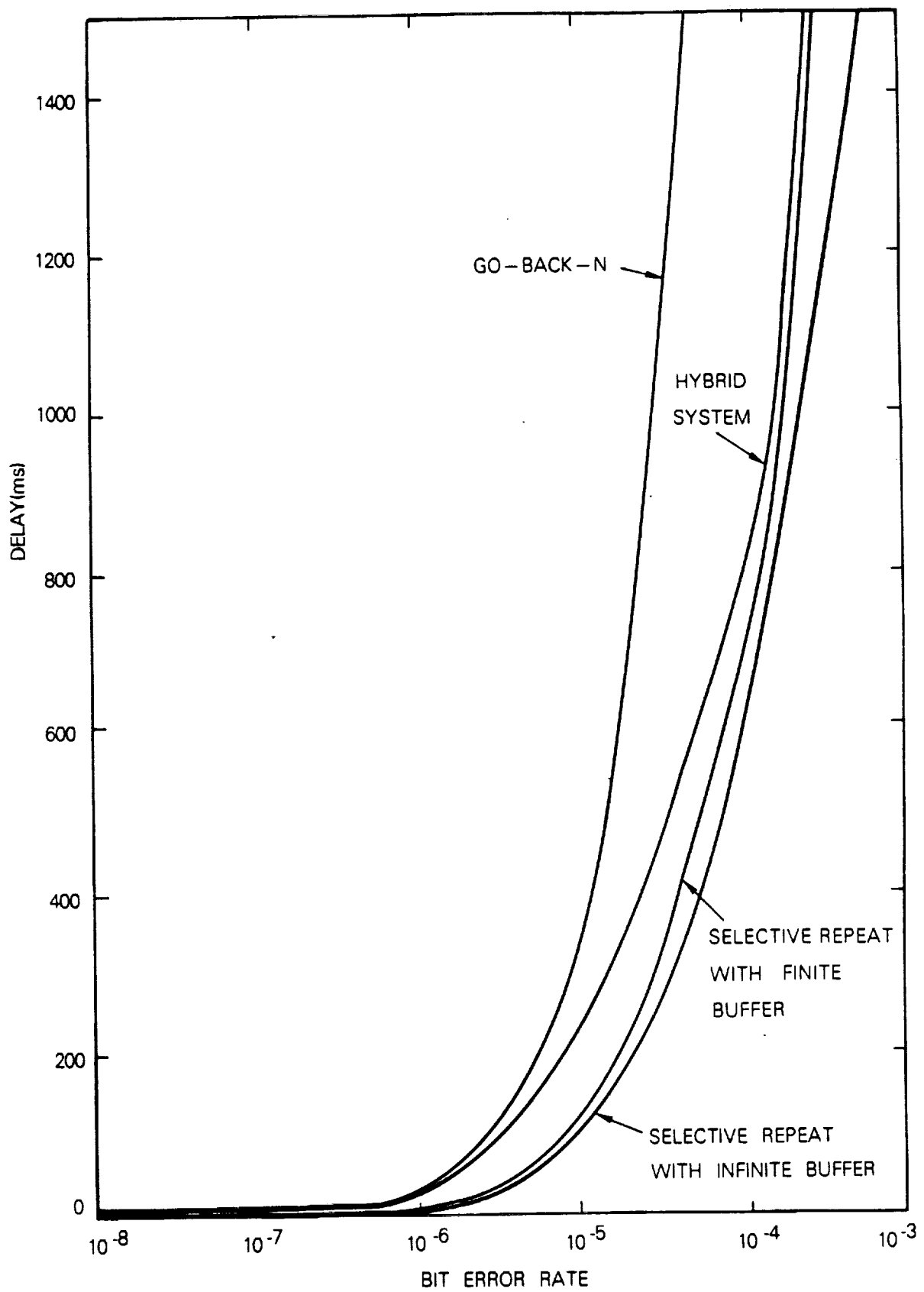
An analysis of a selective acknowledgement protocol procedure for the transport level over single hop satellite links has also been performed[4]. Figure A7 shows the improvement that results. A better than 95% efficiency is achieved over a 1.544 Kbit/s capacity satellite channel using selective acknowledgement compared to only 50% for the ISO/OSI TP-4 method. ISO/OSI is in the process of recommending the selective acknowledgement method of the transport level.



**Figure A3. Throughput Efficiency with 1-kbit Block Size and 64-Kbit/s Channel Capacity**



**Figure A4. Throughput Efficiency with 2-kbit Block Size and 1.544-Mbit/s Channel Capacity**



**Figure A5. ARQ Delay with 1-kbit Block Size and 64-kbit/s Channel Capacity**



**Figure A6. ARQ Delay with 2-kbit Block Size and 1.544-Mbit/s Channel Capacity**

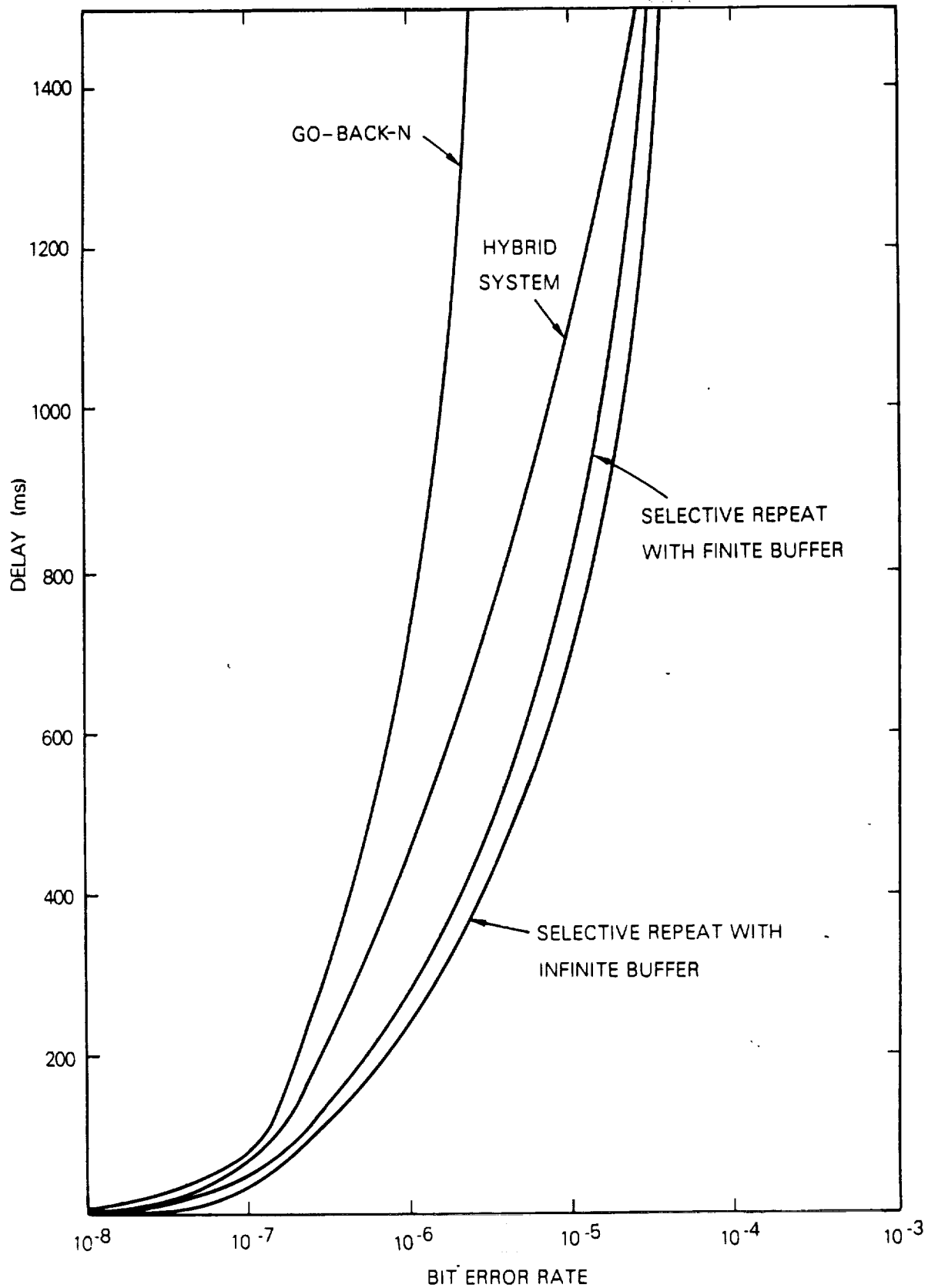
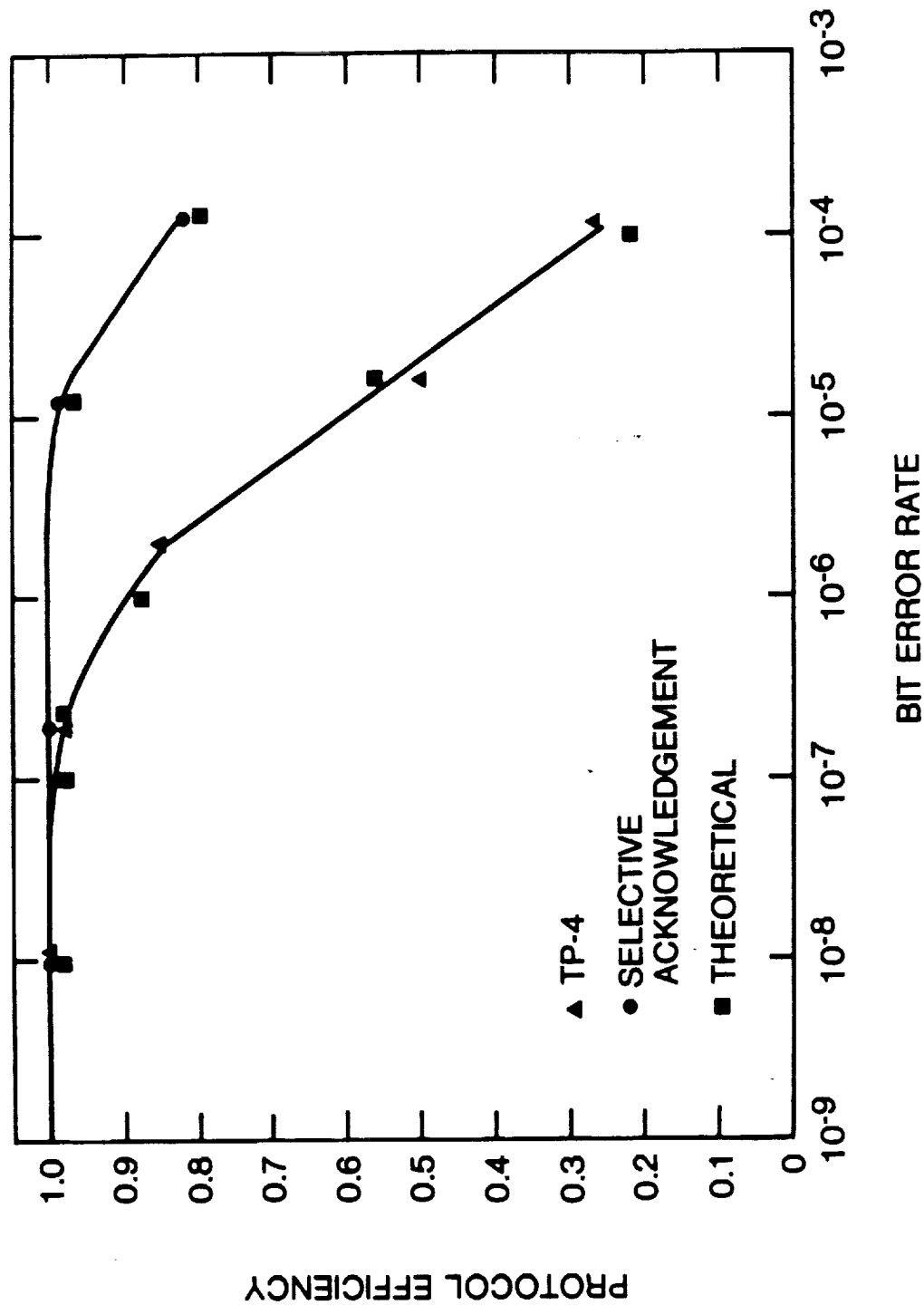


Figure A7. Throughput Efficiency as a Function of BER for Selective Acknowledgement Compared to TP-4



#### A.1.4 CONCLUSIONS

Propagation delay of the magnitude encountered over single and double hop satellite links is not perceived as unacceptable to the user of a remote computer terminal while performing transactions with a remote host computer.

Propagation delay becomes an impediment when the delay interacts with bit error, transmission rate and packet communications protocol. Protocols which require acknowledgement for each message before the next is sent are obviously seriously impacted by the delay even if the link is error free. Protocols which use the Go-back-N procedure operate satisfactorily over satellite links with low error rate but rapidly lose throughput efficiency when error rates and transmission rates are increased. It is those protocols which use some form of selective repeat that retain high throughput at increased error rates and transmission rates that are preferred for computer communications over satellite links.

In both the CCITT and ISO, continued efforts are needed to see to it that computer data communications protocols compatible with satellite propagation delay are adopted. This is a current on-going process that must continue to be supported.

#### A1.5 REFERENCES

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